

N64-23006

# AgRISTARS

**SM-T3-04448**

**NAG 5-31**

A Joint Program for  
Agriculture and  
Resources Inventory  
Surveys Through  
Aerospace  
Remote Sensing

**Soil Moisture**

**September 1982**

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**Semi-annual Report**

**CONSERVB**

**A NUMERICAL METHOD TO COMPUTE  
SOIL WATER CONTENT AND TEMPERATURE  
PROFILES UNDER A BARE SURFACE**

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1. Report No. SM-T3-04448	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Conservb - A Numerical Method to Compute Soil Water Content and Temperature Profiles Under a Bare Surface		5. Report Date September 1982
		6. Performing Organization Code
7. Author(s) C.H.M. van Bavel and R. Lascano		8. Performing Organization Report No. RSC-134
		10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Johnson Space Center Houston, Texas		11. Contract or Grant No. NAG 5-31
		13. Type of Report and Period Covered Semi-annual 3/82-9/82
2. Sponsoring Agency Name and Address Remote Sensing Center Texas A&M University College Station, Texas 77840		14. Sponsoring Agency Code

# 16. Abstract

For evaluating the feasibility of remotely sensing the status of soil moisture, the most promising technology is the measurement of microwave emission by the earth's surface or the backscatter of microwave radiation emitted by an airborne source. In either case, the signals characterize a rather shallow layer, variously estimated between 0.05 and 0.25 m deep. Surface configuration, moisture content, or perhaps more accurately, the specific free energy of the water present, affect not only the signal strength, but also the depth of perception.

A closely related study of the moisture movement and the water balance of deeper layers is indispensable. This classical problem of agricultural and natural hydrology has always been made intractable by the lack of facts on the surface moisture regime. Thus, the two areas of research and application are currently merging. Evidence of this trend is the development of theories, in the form of numerical models, that are combinations of atmospheric and soil physics. These may provide the foundation for models of microwave physics as well as a practical means to interpret radar signatures.

We present here a comprehensive, yet fairly simple model of water disposition in a bare soil profile under the sequential impact of rain storms and other atmospheric influences, as they occur from hour to hour. This model is intended mostly to support field studies of soil moisture dynamics by our current team, to serve as a background for the microwave measurements, and, eventually, to serve as a point of departure for soil moisture predictions for estimates based in part upon airborne measurements.

The main distinction of the current model is that it accounts not only for the moisture flow in the soil-atmosphere system, but also for the energy flow and, hence, calculates system temperatures. Also, the model is of a dynamic nature, capable of supporting any required degree of resolution in time and space.

Much critical testing of the sample is needed before the complexities of the hydrology of a vegetated surface can be related meaningfully to microwave observations.

17. Key Words (Suggested by Author(s))		18. Distribution Statement  Unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 73	22. Price*

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This report describes activity carried out in support of the Soil Moisture Research activities of the Project.

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SEPTEMBER 1982

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## ABSTRACT

Under a contract with the National Aeronautics and Space Administration (NASA, Johnson Space Center in Houston), Texas A&M University, through its Remote Sensing Center, is one of a small group of contractors, evaluating the feasibility of remotely sensing the status of soil moisture.

At present, the most promising technology is the measurement of microwave emission by the earth's surface or the backscattering of microwave radiation emitted by an airborne source. In either case, the signals characterize a rather shallow layer, variously estimated between 0.05 and 0.25 m deep. Surface configuration, moisture content, or perhaps more accurately, the specific free energy of the water present, affect not only the signal strength, but also the depth of perception.

To support such efforts, a closely related study of the moisture movement and the water balance of deeper layers is indispensable. This classical problem of agricultural and natural hydrology has always been made intractable by the lack of facts on the surface moisture regime. Thus, the two areas of research and application are currently merging. Evidence of this trend is the development of theories, in the form of numerical models, that are combinations of atmospheric and soil physics. These may provide the foundation for models of microwave physics as well as a practical means to interpret radar signatures.

As one step in that direction, we present here a comprehensive, yet fairly simple model of water disposition in a bare soil profile under the sequential impact of rain storms and other atmospheric influences, as they occur from hour to hour. This model is intended mostly to support field

studies of soil moisture dynamics by our current team, to serve as a background for the microwave measurements, and, eventually, to serve as a point of departure for soil moisture predictions or estimates based in part upon airborne measurements.

The main distinction of the current model is that it accounts not only for the moisture flow in the soil-atmosphere system, but also for the energy flow and, hence, calculates system temperatures. Also, the model is of a dynamic nature, capable of supporting any required degree of resolution in time and space.

This work is the precursor of similar work for vegetated areas. It should be emphasized, however, that much critical testing of the simple case is needed before the complexities of the hydrology of a vegetated surface can be related meaningfully to microwave observations.

The present model is given in full detail, so as to invite its use by others and to make it possible to make adaptations, changes, and improvements. The program, as listed, can be obtained from the authors in the form of punched cards or a cassette.

## INTRODUCTION

A simulation model is documented for calculating the water content and temperature profiles of a bare soil, from known initial conditions and a set of ordinary, time-dependent weather data, over a period of several days to several weeks. The model is dynamic, because the properties of the system are updated as the temperature and water content are changing in time.

The present model was adapted from a set of algorithms devised for the study of dry mulching as a water conserving treatment in the dryland farming areas of North Texas (Horton, 1977). In turn, the latter model was derived from a simulation of the concurrent flow of water and heat in soil proposed by Van Bavel and Hillel (1975, 1976) and of the infiltration and detention of rainfall suggested by Hillel et al. (1975).

The model provides a comprehensive method for the simultaneous solution of the equation of continuity for water and heat in a soil system. The solution is obtained at frequent, fixed intervals and the moisture and temperature profiles are printed when desired. The distinguishing characteristic of the model is that it does not assume a typical or average rate of evaporation, but that it, rather, generates the instantaneous rate, from the ambient weather and the momentary values of the soil moisture and temperatures. The evaporative flux is found by a combination method, that is, a combination of a surface energy balance and a model of the fluxes above and below that surface.

The model is written in the Continuous System Modeling Program III (CSMP III) language (IBM, 1975), a specific numerical simulation language suitable for time-variant systems. The model was developed for execution on the AMDAHL 470V/6 computer operated by Texas A&M University at

College Station, Texas. This system is operated with the IBM S-370 operating system.

A basic knowledge of physics and FORTRAN is desirable to understand the model. To assist the user, a glossary of variable names with their units has been provided as Appendix A, and a complete listing of the program is presented in Appendix B. Furthermore, since CSMP III is used throughout, a brief explanation will be given when CSMP III statements are used.



## INPUTS AND INITIAL VALUES FOR THE COMPUTER SIMULATION

The inputs to calculate the heat and water balance of a soil system are divided in two parts: constant and variable inputs.

Constant inputs to the model refer to the hydraulic characteristics of the soil and the relationship between albedo (shortwave reflectance) and volumetric water content of the soil surface. The hydraulic characteristics of the soil are the functions relating pressure potential and hydraulic conductivity to volumetric water content.

Variable inputs to the model refer to the time-dependent weather variables. These are:

1. daily global radiation, based on either daily total or hourly data,
2. daily maximum and minimum air temperatures and their corresponding relative humidities, or, hourly temperature and dewpoint data (2.0 m height),
3. average daily wind speed, or hourly data if available (2.0 m height), and
4. amount and duration of precipitation.

Initial values that must be known are the initial soil moisture and heat content of the soil as a function of depth. These are obtained as follows:

1. initial heat content are calculated from an initial measured or estimated soil temperature profile, and
2. initial water contents as measured in the field.

The way in which the constant and time-dependent inputs, and the initial values are manipulated in the model will be considered in detail in section IV of this document.

## DESCRIPTION OF THE SOIL

This simulation model is being applied to describe the heat and water balance of a soil classified in the Norwood series (Mixed (Calcareous), Thermic Typic Udifluvents). Specifically, the hydraulic characteristics in the model were obtained from three unpublished theses from Texas A&M University (Saffaf, 1966; Marek, 1977; and Humphreys, 1979). These reports deal with the field determination of the hydraulic conductivity of the soil and with the hydraulic characteristics of irrigation furrows. The experimental work was done on the Agronomy farm of Texas A&M University, on a Norwood soil.

In terms of its hydraulic characteristics, the soil profile being used in this simulation can be divided into two horizons (Humphreys, 1979). The characteristics of each horizon are listed below:

### A. Horizon number 1:

- |   |                            |
|---|----------------------------|
| a. Depth  | 0.0 - 0.20 m               |
| b. Texture  | silty clay loam            |
| c. Average dry bulk density   | 1.54 g/cm <sup>3</sup>     |
| d. Saturated hydraulic conductivity   | 5.0 x 10 <sup>-7</sup> m/s |
| e. Relationship of pressure potential versus volumetric water content as plotted in Figure 1, and |                            |
| f. Calculated hydraulic conductivity versus volumetric water content as plotted in Figure 2.      |                            |

### B. Horizon number 2:

- |                             |                        |
|-----------------------------|------------------------|
| a. Depth                    | 0.20 - 1.20 m          |
| b. Texture                  | silt loam              |
| c. Average dry bulk density | 1.46 g/cm <sup>3</sup> |

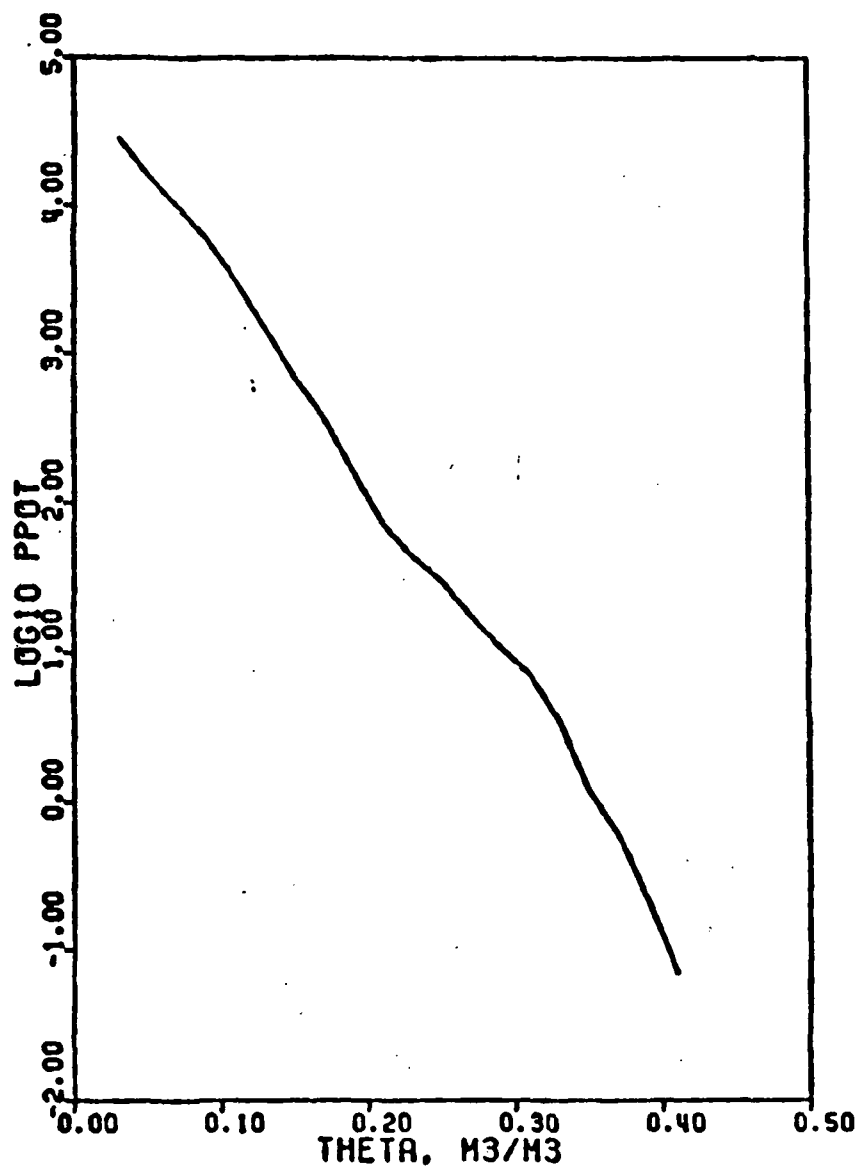


Figure 1. Relationship between the Log<sub>10</sub> of pressure potential (-m of water column) and volumetric water content for the surface horizon, 0.0 - 0.20 m, of the Norwood soil (FUNCTION TVSP1).

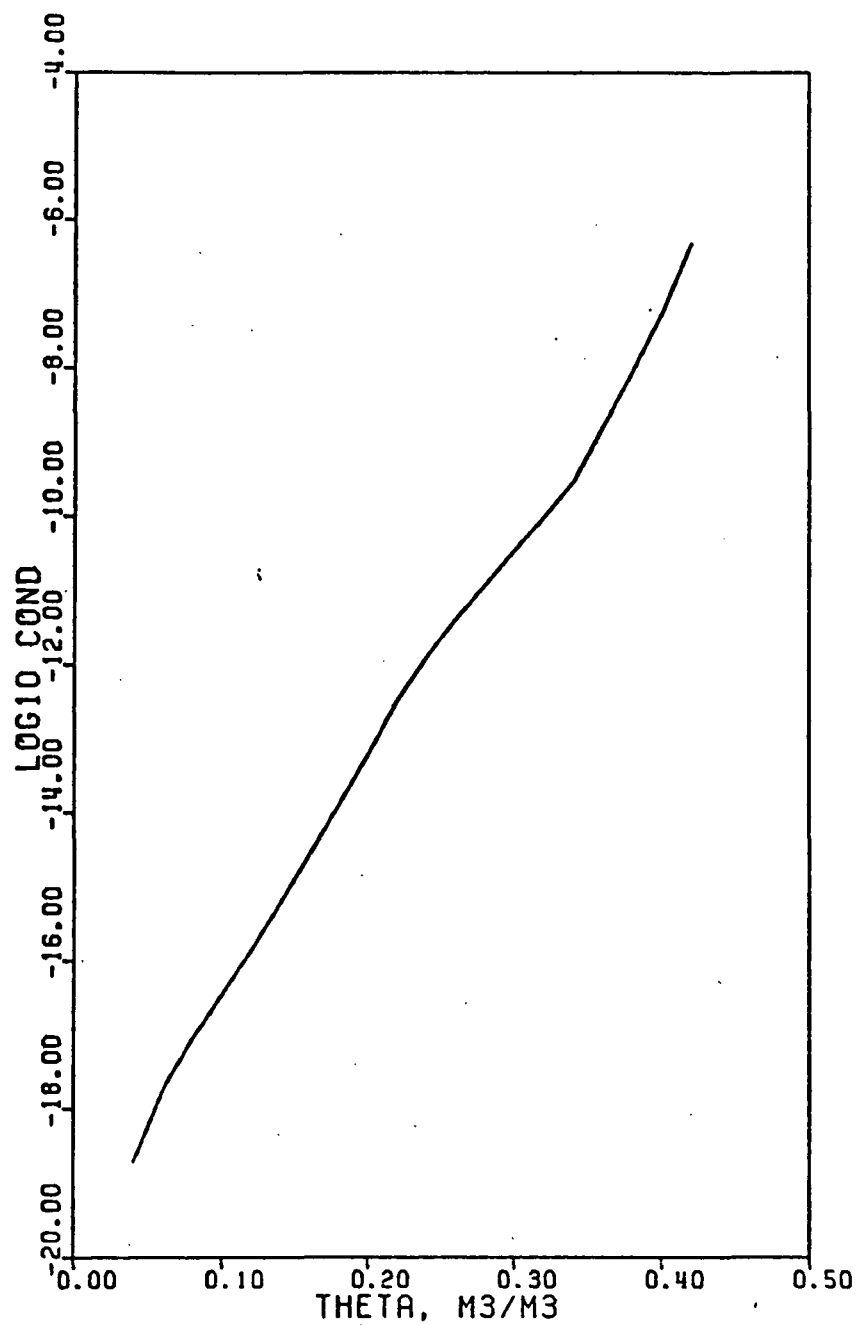


Figure 2. Relationship between the calculated hydraulic conductivity in m/s and the volumetric water content of the surface horizon, 0.0 - 0.20 m, of the Norwood soil (FUNCTION TVSC1).

- d. Average saturated hydraulic conductivity  $6.0 \times 10^{-6}$  m/s
- e. Relationship of pressure potential versus volumetric water content as plotted in Figure 3, and
- f. Calculated hydraulic conductivity versus volumetric water content as plotted in Figure 4.

The hydraulic conductivity as a function of volumetric water content for both horizons was calculated by the method of Jackson (Jackson, 1972). The WATFIV algorithm used for this calculation is included in Appendix C.

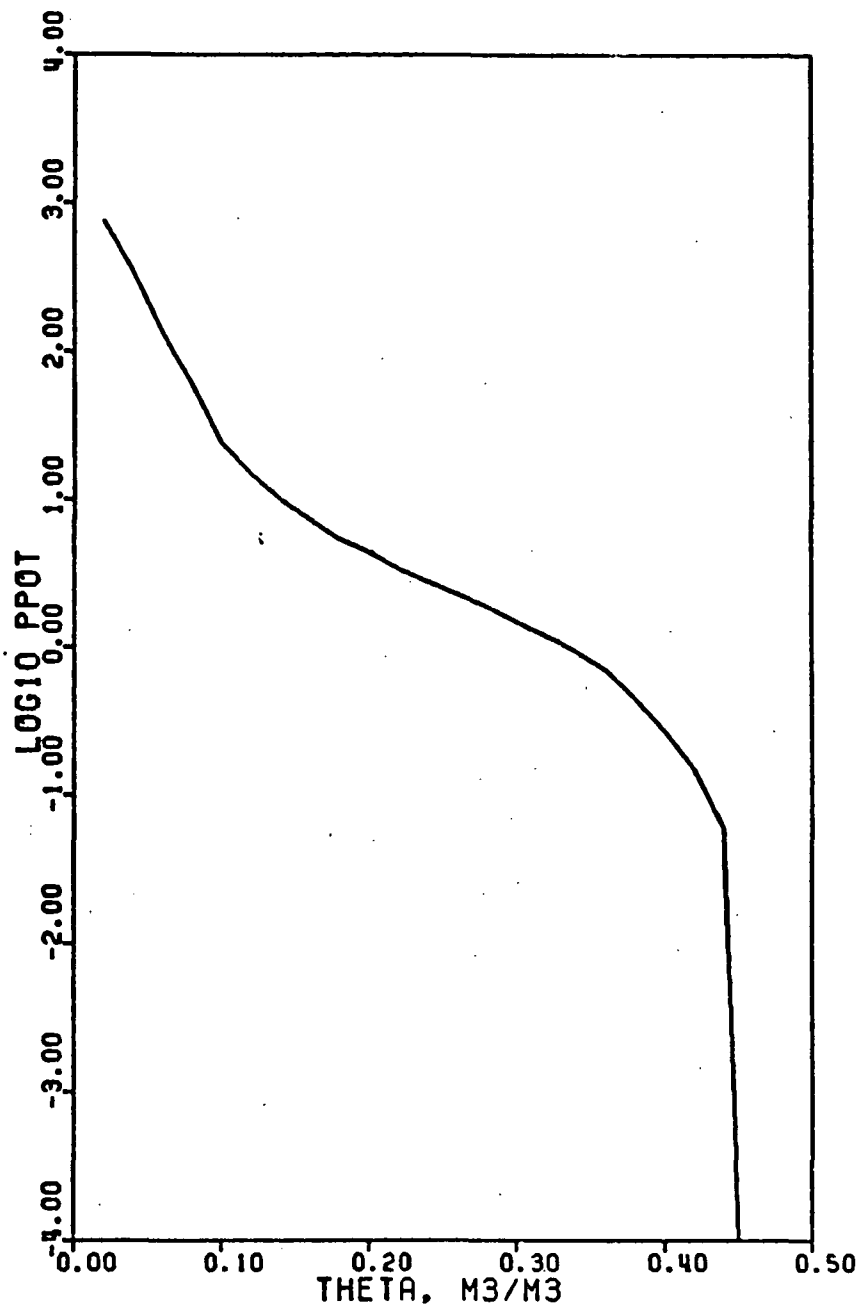


Figure 3. Relationship between the  $\text{Log}_{10}$  of pressure potential (-m of water column) and volumetric water content for the sub-soil horizon, 0.20 - 1.20 m, of the Norwood soil (FUNCTION TVSP2).

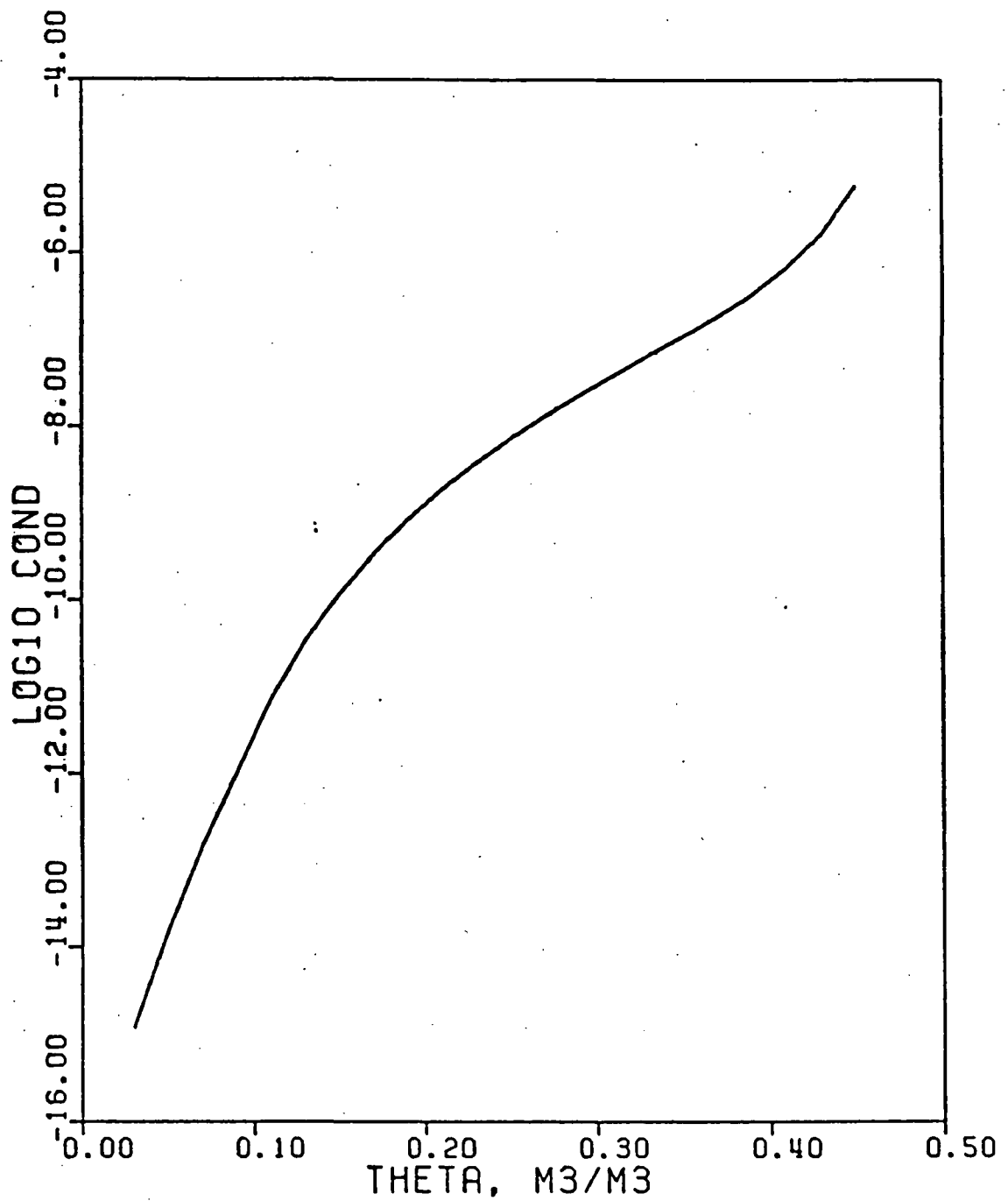


Figure 4. Relationship between calculated hydraulic conductivity in m/s and volumetric water content for the sub-soil horizon, 0.20 - 1.20 m, of the Norwood soil (FUNCTION TVSC2).

## DESCRIPTION OF THE MODEL

### Introduction to CSMP III:

Program statements in CSMP III can be divided into three categories: data, structure, and control statements. Data statements assign numeric values to the parameters, constants, and initial conditions of the system. Structure statements define the functional relationship between the variables of the model. Control statements deal with the duration of the simulation, the integration increment, type of output, and with the translation and execution of the program. The user does not need to specify the category of each statement.

The structure of the program can be divided into three sections: INITIAL, DYNAMIC, and TERMINAL sections. The major characteristics of these translation control statements are the following:

#### INITIAL Section

1. Operations specified in this section are executed only at the onset of the simulation,
2. it contains the equations that define the invariable geometry of the system, and
3. it contains values and tables for specified parameters, and provides the initial values of specified variables.

#### DYNAMIC Section

1. It contains the equations that are needed to update the system at every time interval, and
2. it uses an iterative procedure for the solution of implicit functions of certain variables.



## TERMINAL Section

1. it specifies the finish time for simulation,
2. it specifies the time interval for output and the variables to be printed in the output, and
3. it specifies the method of integration that is to be used and the integration time interval.

## Description

The program will be described in the sequence given in the listing in Appendix B. To assist the user with the identification of variables refer to Appendix A where a glossary of the variables with their corresponding units are given. The International System of Units (SI) is used throughout the program with the exception of water potential values, which are given in terms of m water column. In principle, the water potential should be specified in kPa, but the approximation that  $1 \text{ kPa} = 0.1 \text{ m water column}$  is sufficiently accurate and simplifies the dimensions of the units throughout. For the purpose of the description, the program is divided into five parts:

### JOB CONTROL LANGUAGE (JCL) (lines 4-10)

The JCL statements are the ones used at the Texas A&M University computer installation (AMDAHL 470V/6, IBM S370 system). The user should consult the instructions of the local installation and make the necessary changes. Note that the program requires at least 128K bytes of memory.

## TITLE, MEMORY ORGANIZATION, AND ALLOCATION (lines 16-30)

Lines 16-19 are TITLE statements. This is a CSMP III label statement and allows the user to specify a heading that will appear at the top of the first page of printed output. Lines 14 and 15 are CSMP III comment statements, and can be identified by an asterisk (\*) in column 1. Lines 21-30 are translation control statements to organize the memory and to initialize arrays. Lines 21-23 are the CSMP III STORAGE statement, and they represent subscripted variables with the appropriate number of storage locations contained within the parentheses. Lines 24-27 are DIMENSION statements, and are handled as in FORTRAN with the exception that a virgule (/) must appear in column 1. The virgule indicates that the DIMENSION instruction is a FORTRAN specification statement. Lines 27 and 28 are EQUIVALENCE statements and are treated in the same manner as the DIMENSION statements. The EQUIVALENCE statement allows that the variables within the parentheses be assigned to the same storage locations in the memory, that is, the variables are synonymous. Line 30 are variables specified as integers with the statement FIXED.

## INITIAL Section (lines 36-210)

The INITIAL section begins with the lines (the numbers to the left refer to the corresponding number of the listing in Appendix B):

36. INITIAL

38. NOSORT

The NOSORT is a CSMP III translation control statement and it means that the subsequent statements are to be executed in the order in which they

appear. The INITIAL section will be described in paragraphs as indicated by the comment cards in the listing (Appendix B).

### \*\*\* 1) DEFINITION OF PARAMETERS (lines 40-50)

Lines 40 and 42-50 are data control statements. The PARAMETER statement (lines 40-50) is used to assign numerical values to the following variables (the number to the right in parenthesis refers to the corresponding number of the variable as given in the glossary in Appendix A):

40.	PARAMETER	NL	= 13	(68)
42.	PARAMETER	KONDS	= 4.20	(61)
43.	PARAMETER	KNODW	= 0.57	(63)
44.	PARAMETER	KONDA	= 0.025	(60)
45.	PARAMETER	VHCAPS	= 1.925E-06	(102)
46.	PARAMETER	VHCAPW	= 4.186E06	(103)
47.	PARAMETER	SIGMA	= 5.67E-08	(82)
48.	PARAMETER	ZO	= 0.01	(108)
49.	PARAMETER	SATCON	= 0.60E-06	(80)
50.	PARAMETER	PORSTY	= 0.50	(71)

The values for the heat conductivity of soil (KONDS), water (KONDW), heat conductivity by air (KONDA) and volumetric heat capacity of the soil (VHCAPS) and of water (VHCAPW) were obtained as suggested by De Vries (1966).

The value for the total porosity (PORSTY) of the soil was calculated from the average dry bulk density of the soil layers i.e.

$$\text{PORSTY} = 1.0 - \frac{\text{Average dry bulk density}}{\text{Particle density}}$$

### \*\*\* 2) DAILY COUNTERS (lines 52-54)

Lines 52-54 initialize day counters, which are used to keep track of the daily input data that is read with lines 56-61 in the third paragraph.

### \*\*\* 3) READ INPUT DATA (lines 56-61)

The input data is stored in a two dimensional array (WINPUT), and is

read in with a FORTRAN READ statement (line 57).

\*\*\* 4) SPECIFICATION OF THE GEOMETRY OF THE SYSTEM, INITIAL WATER CONTENT  
AND TEMPERATURE (lines 64-68)

In CSMP III, the TABLE statement is used to assign values to the subscripted variables listed on a STORAGE card. Thus, lines 64, 66, and 67 are used to initialize the values for the thickness of the compartment (TCOM), initial volumetric water content (ITHETA), and initial soil temperatures (ITEMP). Since the number of layers (NL) is 13, one value for each soil layer must be specified with the TABLE statement. Three periods (...) are used as continuation to following lines.

\*\*\* 5) CALCULATIONS OF DISTANCE AND DEPTH (lines 70-75)

The depth (DEPTH(I)) and the distance (DIST(I)) of each soil layer is calculated in lines 70-75. The depth of each layer is the vertical distance between its midpoint and the soil surface, and the distance between midpoint of adjacent layers is given by DIST(I) (lines 72-75). The depth of the first layer (DEPTH(1)) is half its thickness (line 70), and the distance of the first layer (DIST(1)) is set equal to its depth (line 71).

```
70.      DEPTH(1) = 0.5*TCOM(1)
71.      DIST(1) = DEPTH(1)
72.      DO 20 I = 2,NL
73.      DIST(I) = 0.5*(TCOM(I-1)+TCOM(I))          (21)
74.      DEPTH(I) = DEPTH(I-1)+0.5*(TCOM(I-1)+TCOM(I))  (17)
75. 20 CONTINUE
```

Figure 5 shows the geometry of the system and symbols used in the program, and Table 1 lists the corresponding values of TCOM, DIST, and DEPTH.

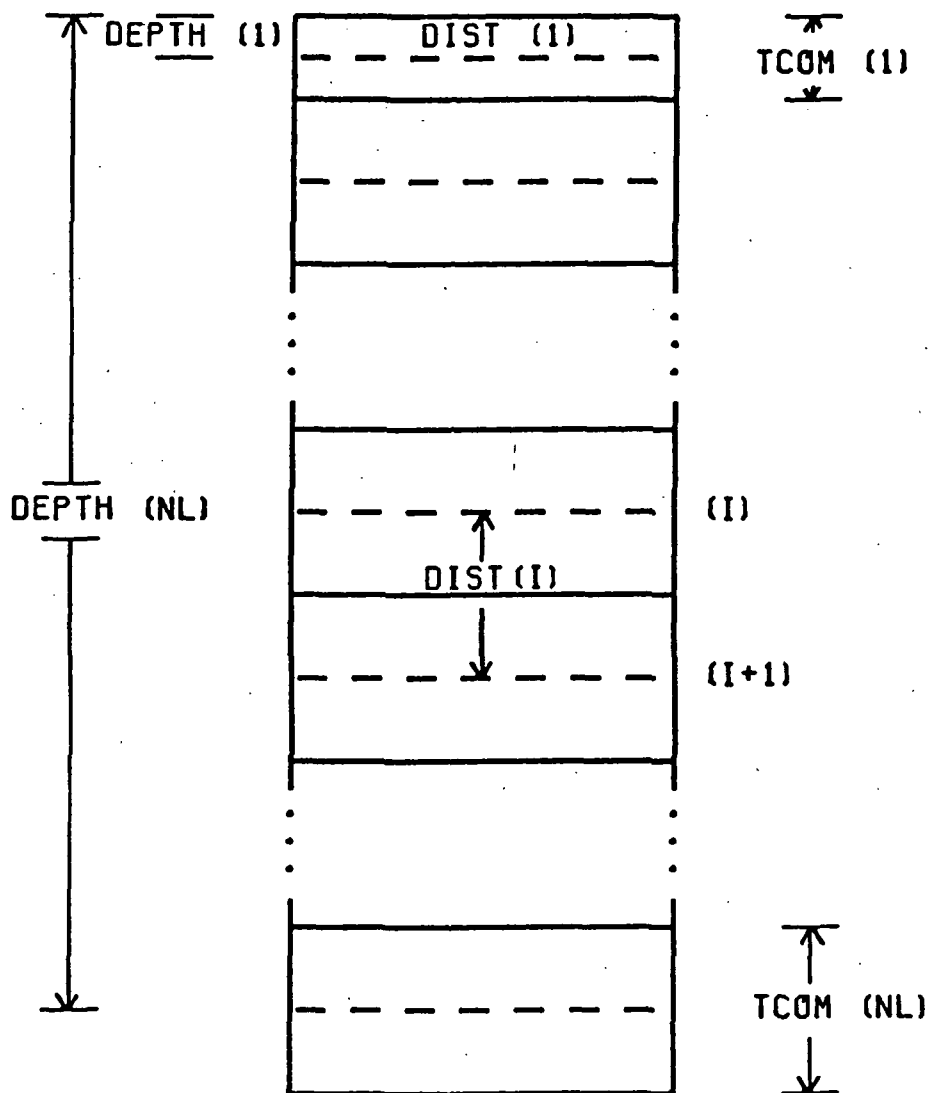


Figure 5. Geometry of the system and symbols used in the program.

TABLE 1. Invariable geometry of the soil system.

Layer N	Thickness of compartment	Distance	Depth
(I)	TCOM(I) (m)	DIST(I) (m)	DEPTH(I) (m)
1	0.01	0.005	0.005
2	0.02	0.015	0.020
3	0.02	0.020	0.040
4	0.03	0.025	0.065
5	0.03	0.030	0.095
6	0.04	0.038	0.130
7	0.05	0.045	0.175
8	0.05	0.050	0.225
9	0.10	0.075	0.300
10	0.10	0.100	0.400
11	0.15	0.125	0.525
12	0.30	0.225	0.750
13	0.30	0.300	1.050

\*\*\* 6) CALCULATIONS OF INITIAL WATER AND TEMPERATURE CONDITIONS (lines 79-87)

From the parameters given, the following initial conditions for water and temperature in the soil system are calculated:

1) the initial volumetric heat capacity of each soil layer (IVHCAP(I)) is calculated from the soil porosity and its water content as suggested by De Vries (1966).

$$81. \quad IVHCAP(I) = VHCAPW * ITHETA(I) + (1.0 - PORSTY) * VHCAPS \quad (54)$$

2) the initial water content (IWATER) for the entire soil profile is calculated by,

$$82. \quad IWATER = IWATER + TCOM(I) * ITHETA(I) \quad (57)$$

3) the initial volume of heat of each soil layer (IVOLH (I)) is calculated by,

$$83. \quad IVOLH(I) = ITEMP(I) * TCOM(I) * IVHCAP(I) \quad (55)$$

4) the net difference between influx and outflux of soil water (NFLUX) and inflow and outflow of heat (NFLOW) is set equal to zero respectively by,

$$84. \quad NFLUX(I) = 0.0 \quad (67)$$

$$85. \quad NFLOW(I) = 0.0 \quad (66)$$

5) and the initial volume of water in each soil layer (IVOLW(I)) is calculated by,

$$86. \quad IVOLW(I) = ITHETA(I) * TCOM(I) \quad (56)$$

In CSMP III, a graphical relationship between pairs of x - y coordinates can be represented by the data control statement FUNCTION. Thus, lines 93, 116, 139, 164, 188, and 198 represent the following relationships:

1) FUNCTION TVSP1: Volumetric water content versus pressure potential. These data characterize the first soil horizon as given in Figure 1.

2) FUNCTION TVSC1: Volumetric water content versus calculated hydraulic conductivity. These data characterize the first soil horizon as

given in Figure 2.

3) FUNCTION TVSP2: Volumetric water content versus pressure potential. These data characterize the second soil horizon as given in figure 3.

4) FUNCTION TVSC2: Volumetric water content versus calculated hydraulic conductivity. These data characterize the second soil horizon as given in figure 4.

5) FUNCTION TEVSKO: Soil temperature versus heat conductivity by water vapor. This relationship is plotted in Figure 6.

6) FUNCTION TIVSAL: Volumetric water content of the first soil layer versus albedo (shortwave reflectance). This relationship is plotted in Figure 7.

\*\*\* 7) TABLE OF THE GEOMETRY OF THE SYSTEM AND ITS INITIAL STATE  
(lines 206-210)

The INITIAL section ends with an output of a table of the geometry of the system as given in Table 1.

DYNAMIC Section (lines 216-428)

The equations which update the system at every time interval and to perform integrations are given in the DYNAMIC section. The DYNAMIC section will be described in paragraphs as indicated by the comment cards in the listing (Appendix B).

The DYNAMIC section begins with the lines,

216. DYNAMIC

218. NOSORT



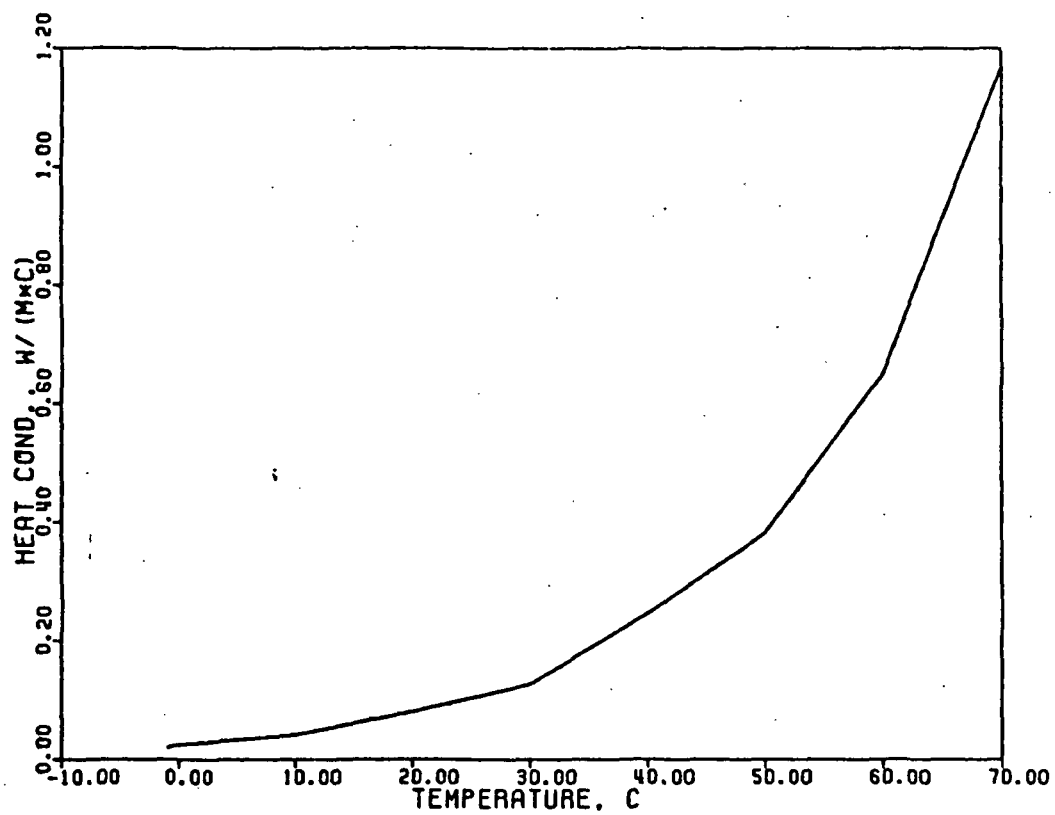


Figure 6. Heat conductivity by water vapor versus soil temperature (FUNCTION TEVSKO).

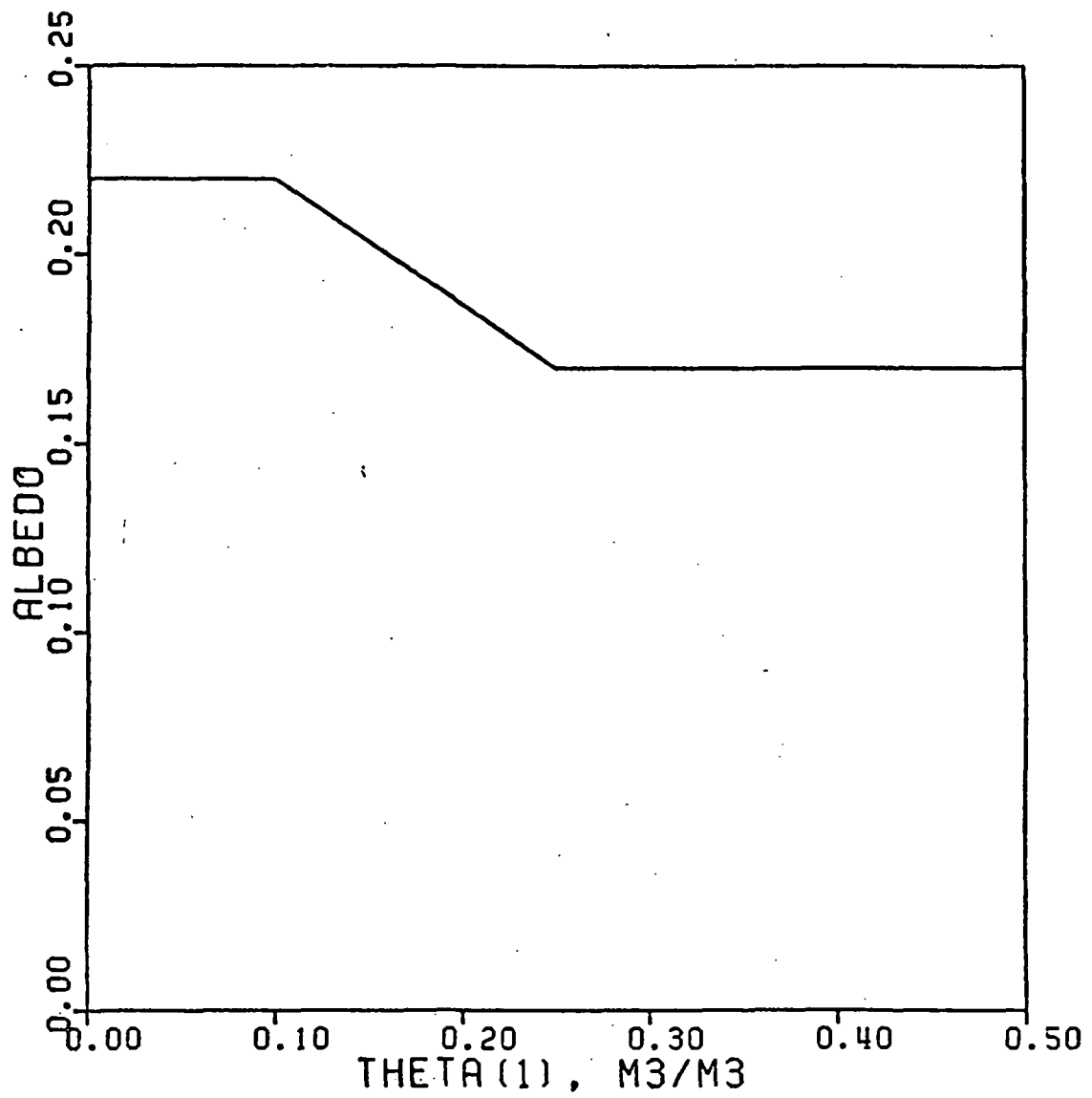


Figure 7. Albedo versus volumetric water content of first soil layer (FUNCTION T1VSAL).

As explained before, the NOSORT statement indicates that the statements are executed in the order in which they are listed.

The paragraphs are:

\*\*\* 1) DEFINITION OF TIME RELATED VARIABLES (lines 221-230)

This paragraph defines the time related variables: time in hours (HTIME) and standard time of the day in hours (STIME). Also defined is an impulse generator (IMPULS).

223.       Y = IMPULS(86400., 86400.)

which increments the day index (DNUM), which is used to reference WINPUT. The first value in parentheses in the IMPULS statement is the time in seconds to the first pulse, and the second value is the time interval in seconds between pulses.

The variables DNUM, DNUM1, and DNUM2 are daily counters that are used to keep track of the input data read from the array WINPUT where the data are stored. The method used to determine to what Julian day number (JDNUM) the input data corresponds is given by line 230.

230.       JDNUM = WINPUT(1, DNUM) (58)

\*\*\* 2) CALCULATION OF HYDRAULIC CHARACTERISTICS OF THE FIRST HORIZON (lines 232-237)

The volumetric water content (THETA(I)), hydraulic conductivity (COND(I)), pressure potential (PPOT(I)), and hydraulic potential (HPOT(I)), for the first 8 layers of the soil profile (horizon #1) are calculated from the following equations:

1) THETA(I) of each layer is obtained from the ratio of the volume of water (VOLW(I)) to the layer volume per unit area:

$$233. \quad \text{THETA}(I) = \text{VOLW}(I)/\text{TOOM}(I) \quad (93)$$

2)  $\text{COND}(I)$  at the center of each layer is obtained by linear interpolation of the values in the FUNCTION TVSCI using the water content ( $\text{THETA}(I)$ ) of each layer.

$$234. \quad \text{COND}(I) = \text{AFGEN}(\text{TVSCI}, \text{THETA}(I)). \quad (7)$$

AFGEN (Arbitrary Function GENERator) is a CSMP III statement that allows linear interpolation from a relationship specified with a FUNCTION statement.

3)  $\text{PPOT}(I)$  is obtained by linearly interpolating values in the FUNCTION TVSP1 using  $\text{THETA}(I)$  of each layer.

$$235. \quad \text{PPOT}(I) = \text{AFGEN}(\text{TVSP1}, \text{THETA}(I)). \quad (72)$$

4)  $\text{HPOT}(I)$  is the sum of  $\text{PPOT}(I)$  and the elevation ( $-\text{DEPTH}(I)$ ) of each layer.

$$236. \quad \text{HPOT}(I) = \text{PPOT}(I) - \text{DEPTH}(I) \quad (45)$$

### \*\*\* 3) CALCULATION OF HYDRAULIC CHARACTERISTICS OF SECOND HORIZON

(lines 239-244)

The same calculations outlined in paragraph #2 are performed for the bottom five layers of the soil profile, that is, the second horizon. In this case, FUNCTIONS TVSP2 and TVSC2 are used with the AFGEN statements.

### \*\*\* 4) CALCULATION OF THERMAL PROPERTIES (lines 246-253)

In this paragraph, the volumetric heat capacity ( $\text{VHCAP}(I)$ ), temperature ( $\text{TEMP}(I)$ ), and thermal conductivity ( $\text{KOND}(I)$ ) are calculated for the 13 layers in the soil profile. The equations used are:

1)  $\text{VHCAP}(I)$  is calculated from the porosity ( $\text{PORSTY}$ ) and the water

content (THETA(I)) as suggested by De Vries (1966). Soil air is not considered in the calculation.

$$247. \quad \text{VHCAP}(I) = \text{VHCAPW} * \text{THETA}(I) + (1.0 - \text{PORSTY}) * \text{VHCAPS} \quad (101)$$

2) TEMP(I) of each soil layer is calculated by dividing the volumetric heat content per unit area (VOLH(I)) by the product of volumetric heat capacity (VHVAP(I)) and layer thickness (TCOM(I)).

$$248. \quad \text{TEMP}(I) = \text{VOLH}(I) / (\text{VHCAP}(I) * \text{TCOM}(I)) \quad (91)$$

3) The contribution of the water vapor phase to the thermal conductivity (KONDV) is obtained by linear interpolation of values in FUNCTION TEVSKO and TEMP(I) for each layer.

$$249. \quad \text{KONDV} = \text{AFGEN}(\text{TEVSKO}, \text{TEMP}(I)) \quad (62)$$

4) KOND(I) of each soil layer is found by the formula suggested by De Vries (1966) using the values of KONDS, KONDA, and KONDW assigned in the INITIAL section.

$$250. \quad \text{KOND}(I) = ((1. - \text{PORSTY}) * \text{KONDS} * 0.4 + \text{THETA}(I) * \text{KONDW} + \dots \quad (59) \\ (\text{PORSTY} - \text{THETA}(I)) * 1.4 * (\text{KONDA} + \text{KONDV})) / \dots \\ ((1. - \text{PORSTY}) * .4 + \text{THETA}(I) + (\text{PORSTY} - \text{THETA}(I)) * 1.4)$$

### \*\*\* 5) CALCULATIONS OF AVERAGE CONDUCTIVITIES (lines 255-260)

The average thermal conductivity (AVKOND) and average hydraulic conductivity (AVCOND) for transport between adjacent layers is taken to be the average of layer conductivities, weighted according to their relative thickness.

For the flow of heat, AVKOND(I) is calculated from:

$$256. \quad \text{AVKOND}(I) = (\text{TCOM}(I-1) + \text{TCOM}(I)) / (\text{TCOM}(I-1) / \text{KOND}(I-1) + \text{TCOM}(I) / \text{KOND}(I)) \quad (4)$$

For the flux of liquid water, AVCOND(I) is calculated from:

$$258. \quad AVCOND(I) = (COND(I-1) * TCOM(I-1) + COND(I) * TCOM(I)) / (TCOM(I-1) + TCOM(I)) \quad (3)$$

\*\*\* 6) SPECIFICATIONS OF BOUNDARY CONDITIONS FOR FLOW OF HEAT AND FLUX OF WATER (lines 263-264)

The boundary conditions at the bottom layer (NLL) of the soil profile are defined by the following:

1) The flux of water at the bottom boundary is taken to be equal to the hydraulic conductivity of the bottom layer. That is, the flux of water is driven by unit hydraulic potential gradient

$$263. \quad FLUX(NLL) = COND(NL) \quad (39)$$

2) The flow of heat at the bottom boundary is calculated by Fourier's law assuming that the temperature at 1.20 m depth remains constant, and that this temperature is set equal to ITEMP(NL).

$$264. \quad FLOW(NL) = (TEMP(NL) - ITEMP(NL) * KOND(NL)/TCOM(NL)/2.0) \quad (37)$$

\*\*\* 7) CALCULATION OF FLOW OF HEAT AND FLUX OF WATER (lines 266-269)

The flow of heat between layers is calculated by Fourier's law.

$$267. \quad FLOW(I) = (TEMP(I-1) - TEMP(I)) * AVKOND(I)/DIST(I) \quad (36)$$

The flux of water between layers is calculated by Darcy's law.

$$268. \quad FLUX(I) = (HPOT(I-1) - HPOT(I)) * AVCOND(I)/DIST(I) \quad (33)$$

Note that flow of heat and flux of water is calculated for all layers except the top one.

\*\*\* 8) USE DAILY RAINFALL DATA, AND CALCULATE DAILY RAINFALL DISTRIBUTION (lines 272-285)

The daily rainfall distribution is assumed to follow the pattern illustrated in Figure 8. The necessary inputs to calculate the rainfall distribution are given by,

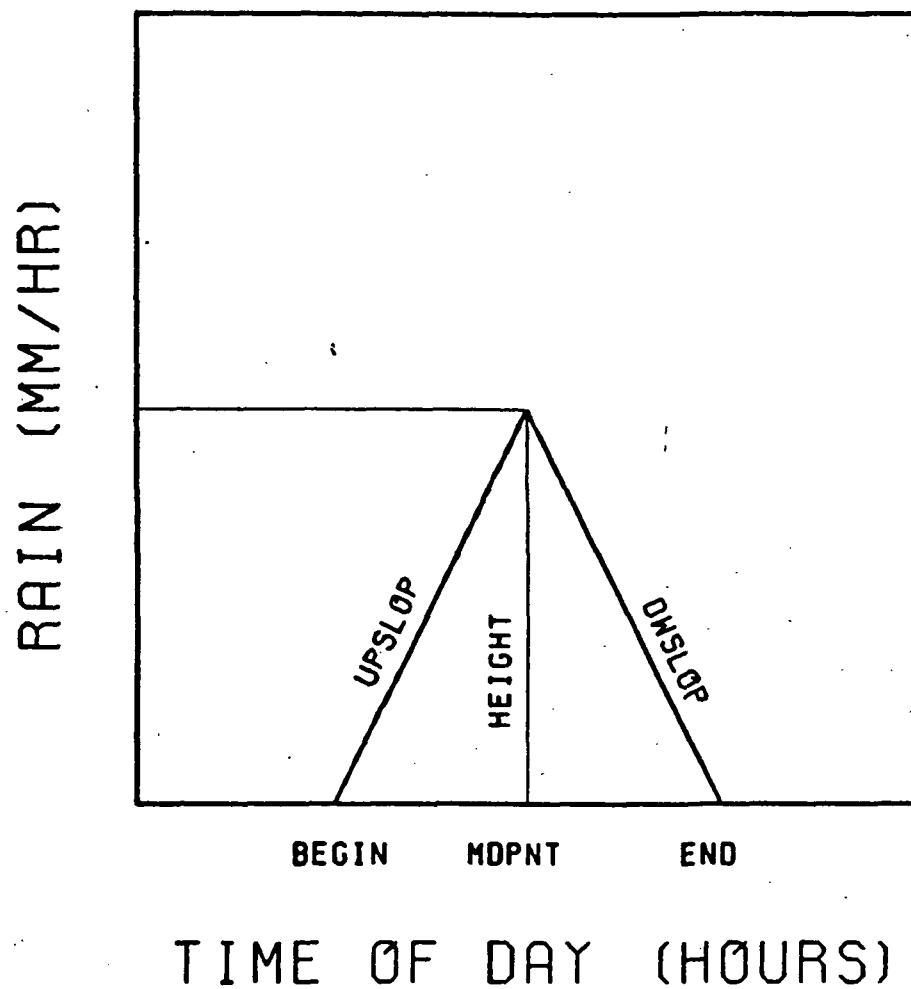


Figure 8. Pattern of daily rainfall distribution. For definition of symbols see text.

```

272.      BEGIN = WINPUT(9, DNUM)                      (6)
273.      END   = WINPUT(10, DNUM)                     (32)
274.      RFT   = WINPUT(11, DNUM)                     (75)

```

The logical branching used to calculate the rainfall distribution as a function of time is illustrated by the flow chart of Figure 9. In the program this is calculated by lines 272-285.

\*\*\* 9) USE DAY LENGTH AND CALCULATE DAILY DISTRIBUTION OF GLOBAL RADIATION (lines 288-292)

The daily distribution of global radiation (GR) is spread out over the daylength (DL) period using a sine function. An example of this distribution is given in Figure 10.

```

290.      GR = 436.33*WINPUT(3, DNUM)/DL * SIN((STIME -12. + DL/2.)      (41)
          *3.141/DL

```

Note: 436.33 is a simplification of  $(24 \times 10^6 / 86400) \times (\pi/2)$

\*\*\*10) CALCULATION OF ALBEDO (lines 294-295)

Albedo (ALB) is obtained by linear interpolation of values in TABLE T1VSAL and the volumetric water content of the first soil layer(T1).

```

294.      T1 = THETA(1)                                          (85)
295.      ALB = AFGEN (T1VSAL, T1)                               (2)

```

\*\*\*11) CALCULATION OF WINDSPEED AND BOUNDARY LAYER RESISTANCE (lines 297-305)

Values of the average windspeed (SA) are set at noon (line 297) and linear interpolation produces values at other times (lines 299-302). The boundary layer resistance (RA) is calculated as the quotient of the logarithm of 2.0 divided by the roughness factor (ZO) squared and the



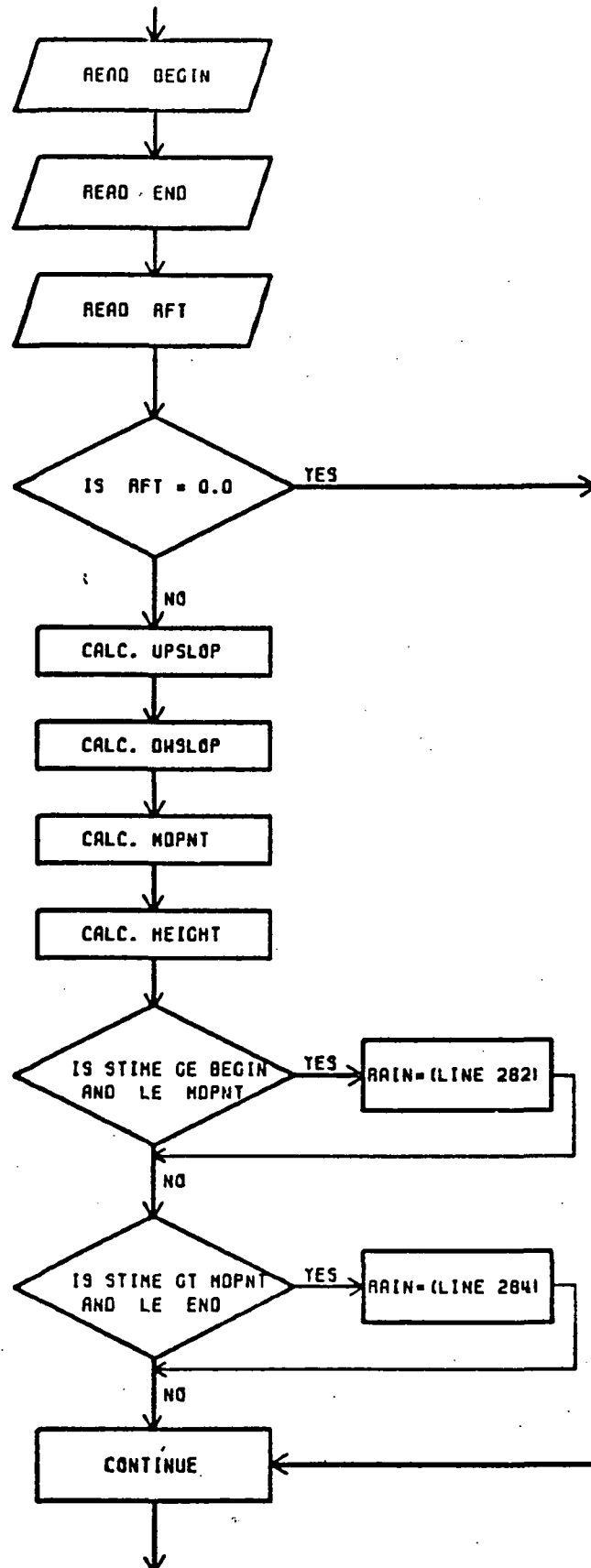


Figure 9. Flow chart showing the logical branching used to calculate the pattern of rainfall distribution.

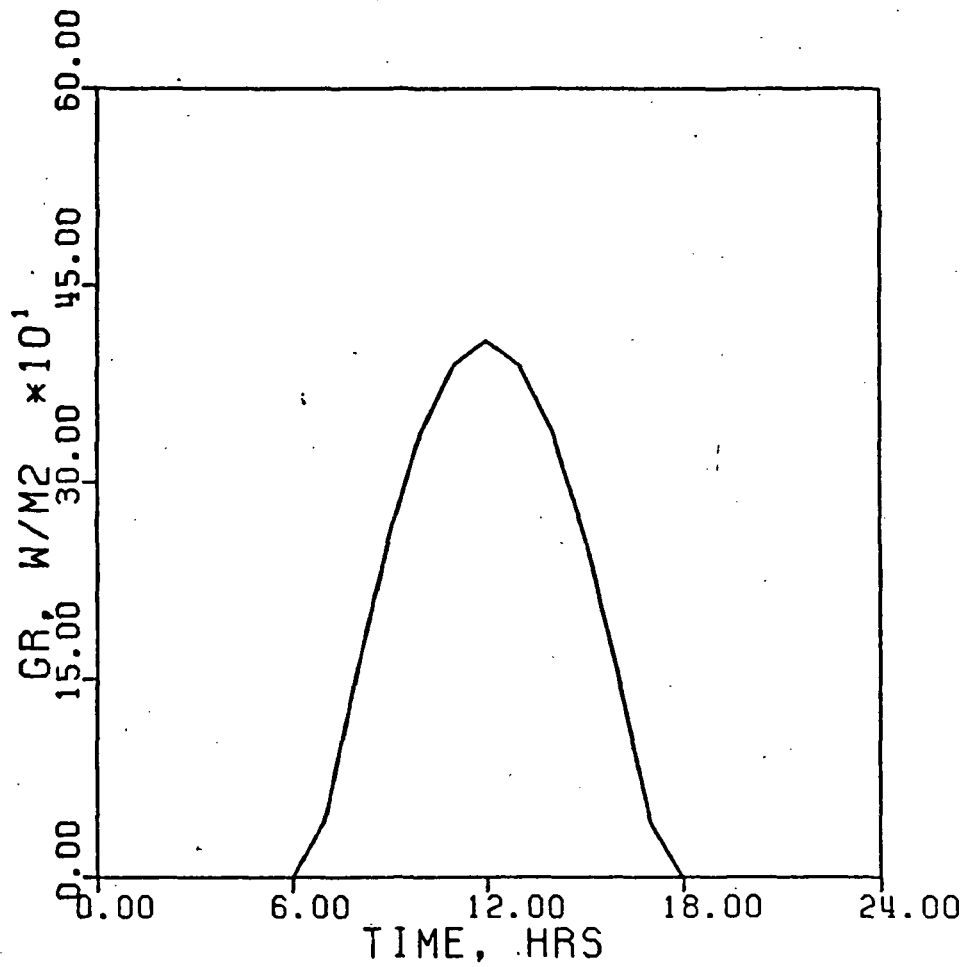


Figure 10. Example of daily distribution of global<sub>2</sub> radiation (GR) over time. (Total irradiance  $10.0 \text{ MJ/m}^2$ , day length = 10.7 hours).

product of windspeed at 2.0 meters and a stability factor (Sellers, 1965).

$$305. \quad RA = (ALOG(2.0/ZO)**2.0)/(0.16*SA) \quad (73)$$

\*\*\*12) CALCULATION OF DEWPOINT TEMPERATURE AND ABSOLUTE HUMIDITY  
(lines 307-314)

Dewpoints at time of minimum air temperature (DPMIN) are set at 5:00 hours standard time and dewpoints at time of maximum air temperature (DPMAX) are set at 15:00 hours standard time allowing linear interpolation of dewpoints (DPTC) at other times (line 311 and 313).

The absolute humidity of the air (HA) is calculated from the equation (Murray, 1967), and is plotted in Figure 11.

$$314. \quad HA = 1.323*EXP(17.27*DPTC/(237.3+DPTC))/(273.16+TAC) \quad (42)$$

\*\*\*13) CALCULATION OF TEMPERATURE OF THE AIR AND VOLUMETRIC HEAT CAPACITY OF THE AIR (lines 316-324)

Minimum air temperature values (TAMIN) are set at 5:00 hours standard time and maximum air temperatures (TAMAX) are set at 15:00 hours standard time allowing linear interpolation of air temperatures (TAC) at other times.

The volumetric heat capacity of the air (SH), as a function of air temperature in degrees Kelvin (TAK) is calculated from the following equation, and is plotted in Figure 12.

$$324. \quad SH = (1154.8*303.16)/(TAK) \quad (81)$$

\*\*\*14) CALCULATION OF SKY IRRADIANCE (line 326)

The sky irradiance (SKL) is found from a formula suggested by Brunt (1932), as modified by Sellers (1965).

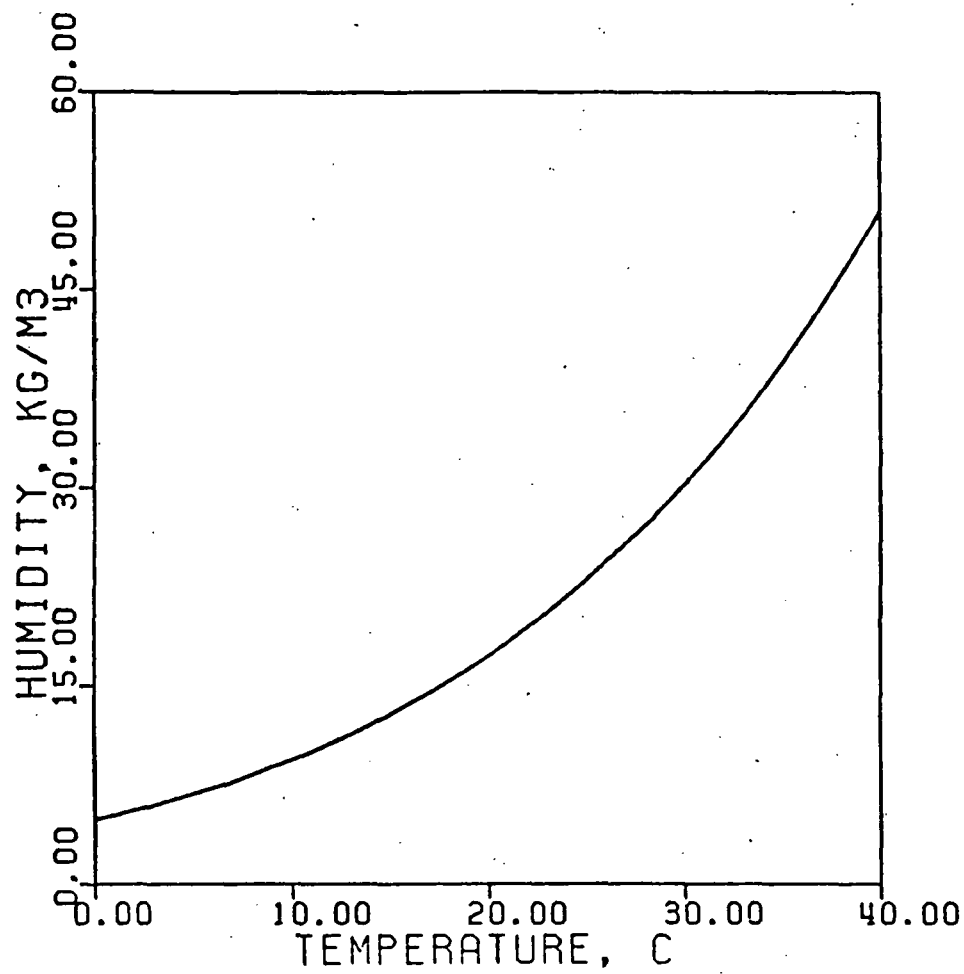


Figure 11. Relationship between absolute humidity of the air (HA) and temperature as calculated with Murray's equation.

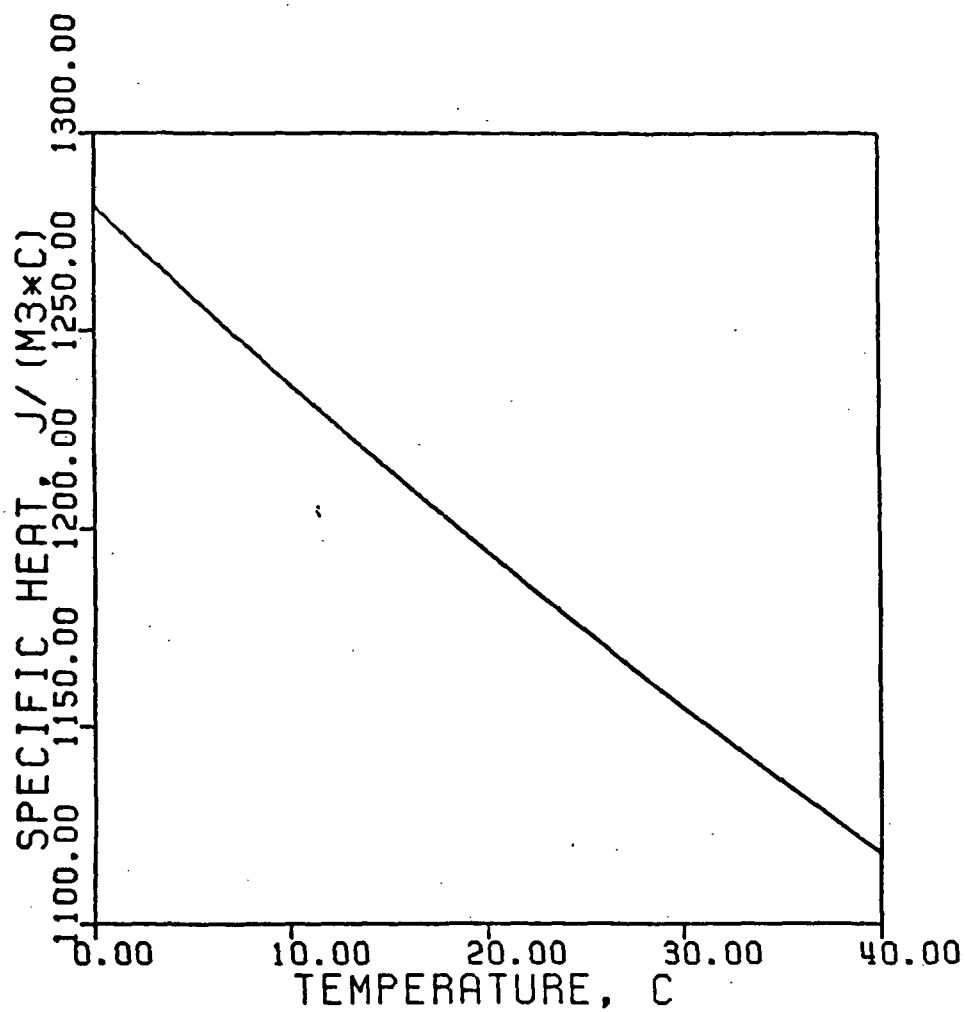


Figure 12. Volumetric heat capacity or specific heat of the air (SH) as a function of temperature.

$$326. \quad SKL = (SIGMA * TAK^{**4}) * (0.605 + 0.039 * SQRT(410. * HA)) \quad (83)$$

\*\*\*15) IMPLICIT CALCULATION OF THE SOIL SURFACE TEMPERATURE (lines 328-335)

The temperature of the soil surface (TSC) is calculated by an implicit function (line 328) using the air temperature (TAC) as a first estimate and calculating the energy balance at the surface:

- 1) Sensible heat flux (A)

$$329. \quad A = (TSC - TAC) * SH / RA \quad (1)$$

- 2) Murray's equation (Murray, 1967) to calculate the saturated humidity (HO) at the soil surface.

$$330. \quad HO = 1.323 * EXP(17.27 * TSC / (273.3 + TSC)) / (273.16 + TSC) \quad (44)$$

- 3) Absolute humidity is calculated as suggested by Van Bavel and Hillel (1976).

$$33. \quad HO = HO * EXP(PPOT(1) / (46.97 * (TSC + 273.16))) \quad (44)$$

- 4) The evaporation (EV) is the quotient of the difference in humidities of surface and atmosphere and the boundary layer resistance.

$$332. \quad EV = (HO - HA) / (RA * 1000.) \quad (33)$$

- 5) The conduction into the soil (S) is calculated as the difference in net radiation and the sum of sensible and latent heat fluxes.

$$333. \quad S = GR * (1. - ALB) + SKL - SIGMA * (TSC + 273.16)^{**4} - A - LH * EV \quad (78)$$

- 6) The final temperature of the soil surface (FTSC) as calculated in the implicit loop is given by Fourier's law for conduction.

$$335. \quad FTSC = TEMP(1) + S * DEPTH(1) / KOND(1) \quad (40)$$

\*\*\*16) CALCULATIONS OF EVAPORATION AND NET RADIATION (lines 337-344)

The flow of heat into the center of layer one (FLOW(1)) is calculated as the product of heat conductivity (KOND(1)) and the differences in surface (TSC) and layer temperatures (TEMP(1)) divided by

distance (DIST(1)).

$$337. \quad \text{FLOW}(1) = (\text{TSC} - \text{TEMP}(1)) * \text{KOND}(1) / \text{DIST}(1).$$

The saturated humidity of the air at the soil surface (HS) is calculated with Murray's equation.

$$338. \quad \text{HS} = 1.323 * \text{EXP}(17.27 * \text{TSC} / (237.3 + \text{TSC})) / (273.16 + \text{TSC}) \quad (46)$$

The absolute humidity (HS) is calculated by,

$$340. \quad \text{HS} = \text{HS} * \text{EXP}(\text{PPOT}(1)) / (46.97 * (\text{TSC} + 273.16)) \quad (46)$$

Evaporation (EVAP) is the quotient of the difference in humidities of soil surface and the atmosphere and the boundary layer resistance.

$$342. \quad \text{EVAP} = (\text{HS} - \text{HA}) / (\text{RA} * 1000.0) \quad (34)$$

The latent heat of vaporization (LH) as a function of the soil surface temperature is given by (Forsythe, 1964).

$$343. \quad \text{LH} = 2.94963\text{E}09 - 2.247\text{E}06 * \text{TSC} \quad (64)$$

and LH as a function of temperature is plotted in Figure 13.

Net radiation (NR) at the soil surface is calculated by difference from the energy balance equation.

$$344. \quad \text{NR} = \text{FLOW}(1) + (\text{TSC} - \text{TAC}) * \text{SH} / \text{RA} + \text{LH} * \text{EVAP} \quad (70)$$

A diagram illustrating the energy and water flux in the top two layers of the soil system is given in Figure 14.

#### \*\*\*17) CALCULATION OF DETAIN, INFILTRATION, AND INCAP (lines 346-359)

The amount of water that remains on the soil surface (DETAIN) is defined as the integral between the initial value and the difference between the rainfall rate (RAIN) and the infiltration rate (INFILT). In CSMP III, this is accomplished by an INTGRL statement.

$$346. \quad \text{DETAIN} = \text{INTGRL}(0.0, \text{RAIN} - \text{INFILT}) \quad (18)$$

The infiltration capacity (INCAP) is the Darcian flux to the center

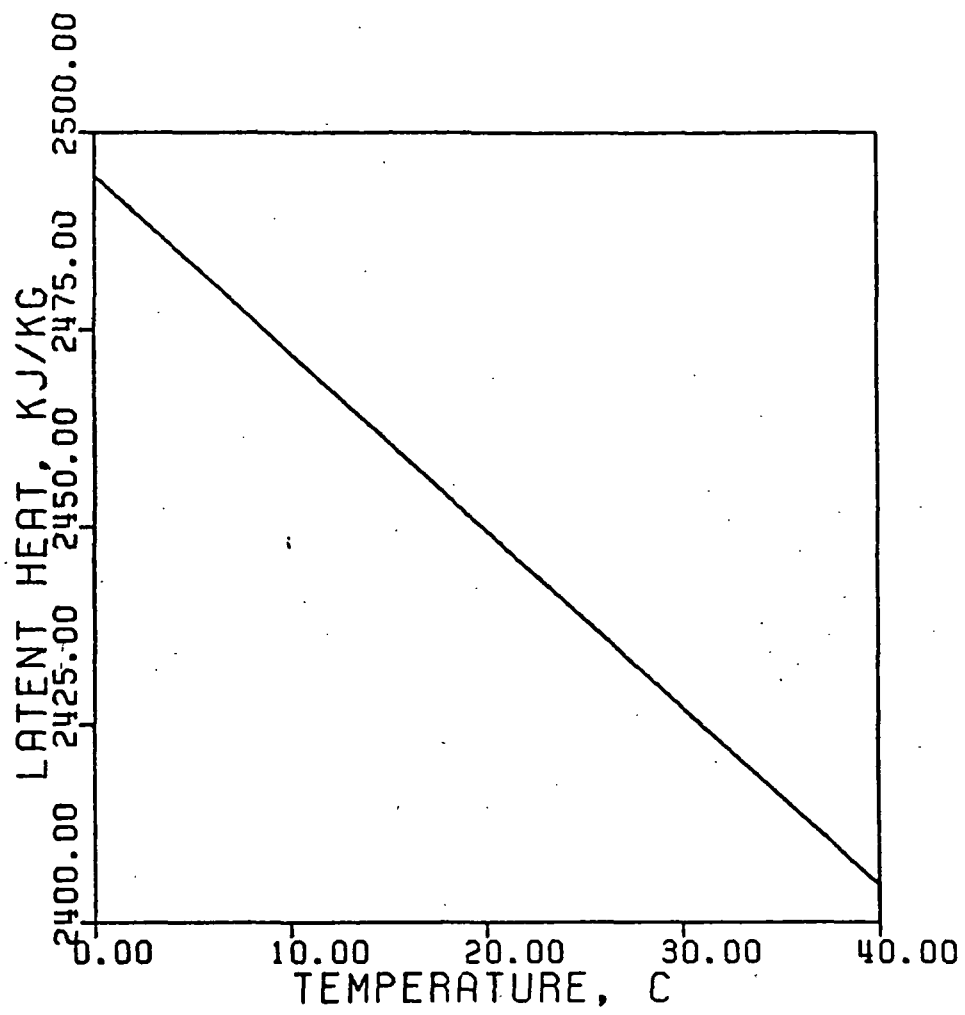


Figure 13. Latent heat of vaporization (LH) as a function of temperature.



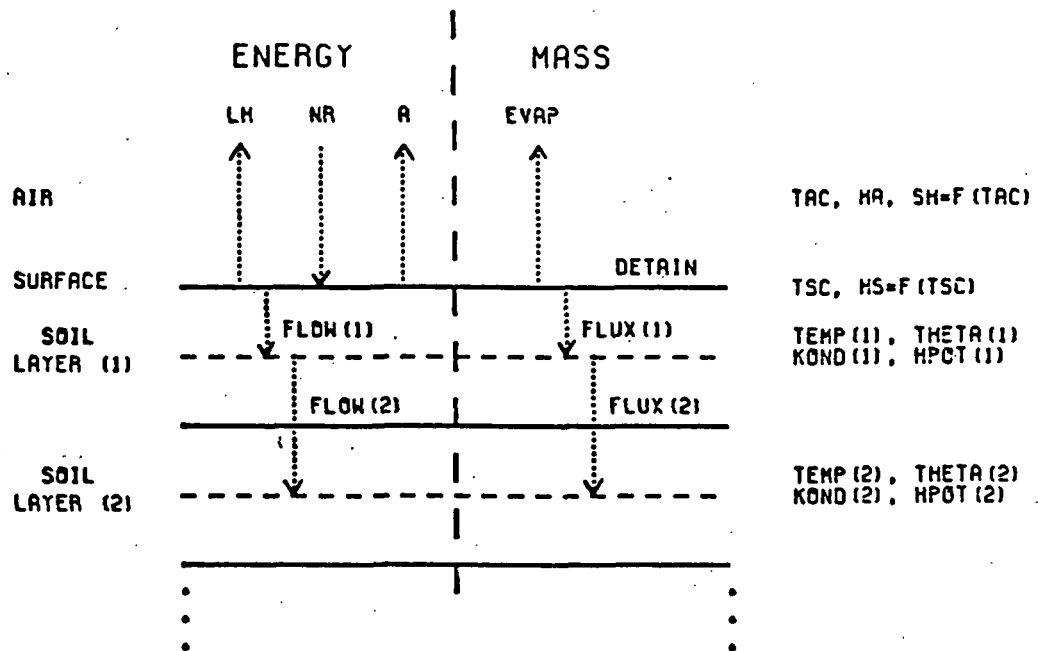


Figure 14. Schematic diagram of the energy and mass flux in the top two layers of the soil system.

of the first layer from the saturated soil surface, at which the pressure potential is assigned a value of zero.

$$347. \quad \text{INCAP} = (0.0 - \text{HPOT}(1)) * 0.5 * (\text{SATCON} + \text{COND}(1)) / \text{DIST}(1) \quad (49)$$

Since the model assumes no runoff, only two possibilities exist with rainfall, and these are:

1) When the rainfall rate does not exceed the infiltration capacity and there is no detention on the soil surface, then the rainfall rate controls the infiltration rate.

$$358. \quad \text{IF}(\text{RAIN.LT.INCAP.AND.DETAIN.LE.0}) \text{ INFILT}=\text{RAIN}$$

2) When the rainfall rate exceeds the infiltration capacity of the soil and water is detained on the soil surface, the infiltration capacity controls the infiltration rate.

$$357. \quad \text{INFILT} = \text{INCAP} \quad (51)$$

The logical branching of the above calculations is illustrated by the flow chart in Figure 15.

### \*\*\*18) CALCULATION OF NET FLOW OF HEAT AND NET FLUX OF WATER (lines 361-365)

The flux of water into the middle of the soil surface layer is equal to the difference in the rate of infiltration and the rate of evaporation.

$$361. \quad \text{FLUX}(1) = \text{INFILT} - \text{EVAP}$$

The heat flow into the bare soil surface ( $\text{FLOW}(1)$ ) was previously defined as,

$$337. \quad \text{FLOW}(1) = (\text{TSC} - \text{TEMP}(1)) * \text{KOND}(1) / \text{DIST}(1)$$

The flux of water ( $\text{FLUX}(I)$ ) and flow of heat ( $\text{FLOW}(I)$ ) for the rest of the layers must obey the continuity equation that is,

$$\text{NFLOW}(I) = \text{FLOW}(I) - \text{FLOW}(I-1) \quad (66)$$

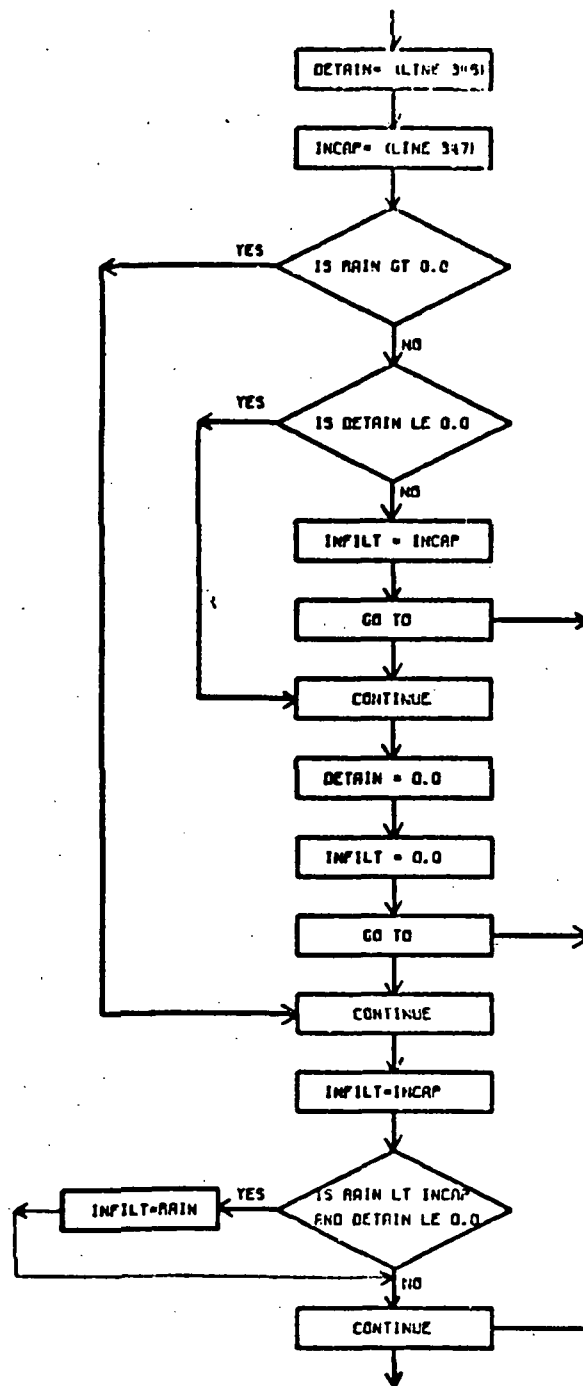


Figure 15. Flowchart showing the logical branching used to calculate INFILT and DETAIN.

$$NFLUX(I) = FLUX(I) - FLUX(I+1)$$

(67)

\*\*\*19) INTEGRATION OF VOLUMETRIC HEAT CONTENT AND VOLUMETRIC WATER  
CONTENT (lines 368-369)

The 13 integrations to keep track of the volumetric heat contents (VOLH(I)) and volumetric water contents (VOLW(I)) are carried out by the CSMP III INTGRL function.

$$368. \quad VOLH1 = INTGRL(IVOLH1, NFLOW1, 13) \quad (105)$$

$$369. \quad VOLW1 = INTGRL(IVOLW1, NFLUX1, 13) \quad (106)$$

The third argument of the integral function indicates that there are 13 integrals to keep track of the volumetric heat content and water content of the 13 layers. The heat contents are stored in an array VOLH(I) and the water contents are stored in an array VOLW(I). Note that these arrays are named in the INITIAL section (lines 28 and 29). The first argument of the integral function states that the initial value of the volumetric heat content and volumetric water content is given by an array IVOLH(I) and IVOLW(I), respectively. The second argument states that the flow and flux rate into the integral is given by the array NFLOW(I) for heat and NFLUX(I) for water.

\*\*\*20) CALCULATION OF CUMULATIVE RAIN, INFILTRATION, EVAPORATION, AND  
DRAINAGE (lines 372-375)

Cumulative rain (CUMRN), cumulative infiltration (CUMINF), cumulative evaporation (CUM EVP), and cumulative drainage (CUMDRN) are calculated with the CSMP III INTGRL function.

$$372. \quad CUMRN = INTGRL(0.0, RAIN) \quad (11)$$

$$373. \quad CUMINF = INTGRL(0.0, INFILT) \quad (10)$$

$$\text{CUMEVP} = \text{INTGRL}(0.0, \text{EVAP}) \quad (9)$$

$$375. \quad \text{CUMDRN} = \text{INTGRL}(0.0, \text{FLXNLL}) \quad (8)$$

\*\*\*21) CALCULATION OF TOTAL WATER FOR DIFFERENT LAYERS (lines 377-392)

The integrated volume of water in the profile, from a given depth to the bottom of the profile, is the sum of the volume of water in each layer starting at the specified depth.

1) From 0.0 - 1.20 m (CUMWTR) (I=1, NL)

$$382. \quad \text{CUMWTR} = \text{CUMWTR} + \text{VOLW}(I) \quad (12)$$

2) From 0.13 - 1.20 m (CUMWT1) (I = 6, NL)

$$385. \quad \text{CUMWT1} = \text{CUMWT1} + \text{VOLW}(I) \quad (13)$$

3) From 0.30 - 1.20 m (CUMWT2) (I=9, NL)

$$388. \quad \text{CUMWT2} = \text{CUMWT2} + \text{VOLW}(I) \quad (14)$$

4) From 0.75 - 1.20 m (CUMWT3) (I=12, NL)

$$391. \quad \text{CUMWT3} = \text{CUMWT3} + \text{FLOW}(I) \quad (15)$$

\*\*\*22) CALCULATION OF DAILY TOTALS (lines 394-404)

The daily totals of infiltration (DINF), rain (DRN), evaporation (DEVP), and drainage (DDRN) are calculated by difference from the accumulated totals and the values at the previous midnight.

$$400. \quad \text{DINF} = \text{CUMINF} - \text{INF}(\text{DNUM} - 2) \quad (20)$$

$$401. \quad \text{DRN} = \text{CUMRN} - \text{RN}(\text{DNUM} - 2) \quad (30)$$

$$402. \quad \text{DEVP} = \text{CUMEVP} - \text{EVP}(\text{DNUM} - 2) \quad (19)$$

$$403. \quad \text{DDRN} = \text{CUMDRN} - \text{DRAIN}(\text{DNUM} - 2) \quad (16)$$

The daily totals are calculated only at the end of a day and the calculations are controlled by the IMPULS statement.

$$394. \quad \text{ZBHJS} = \text{IMPULS}(86400., 86400.),$$

\*\*\*23) CHECK WATER BALANCE (line 406)

The water balance for the soil system (BALANS) is calculated as the difference in the sum of cumulative water in the profile (CUMWTR), cumulative evaporation (CUMEVP), and cumulative drainage (CUMDRN) and the sum of the initial water content (IWATER) and the cumulative infiltration (CUMINF).

$$406. \quad \text{BALANS} = \text{CUMWTR} - \text{IWATER} - \text{CUMINF} + \text{CUMEVP} + \text{CUMDRN} \quad (5)$$

The deviation of BALANS from zero provides an indication of the error produced in the solution of the equations in the model.

\*\*\*24) OUTPUT OF DESIRED VARIABLE (lines 408-428)

The last paragraph of the DYNAMIC section deals with output of calculated variables. Specifically, the following variables are printed at 8:00 and 16:00 hours, standard time: DEPTH(I), THETA(I), PPOT(I), FLUX(I), NFLUX(I), and TEMP(I)

The output at 8:00 hours is controlled by the IMPULS statement.

$$408. \quad Z = \text{IMPULS}(28800.0., 86400.)$$

and the output at 16.0 hours is controlled by the IMPULS statement.

$$425. \quad ZZ = \text{IMPULS}(57600.0., 86400.0)$$

TERMINAL Section (lines 433-466)

The terminal section is mainly composed of execution control statements. The statements that appear in the TERMINAL section are:

$$1) \quad \text{TIMER} \quad \text{FINTIM} = 259200., \text{PRDEL} = 84600.0, \text{DELT} = 100.0$$

The TIMER card is used to specify the variables that control the run-time, print increment, and integration interval (step-size):

a) FINTIM determines the value of TIME (independent variable) at which the run is terminated. FINTIM is set equal to the desired simulation time.

b) PRDEL. This TIMER variable controls the increment for the output of the PRINT statement.

c) DELT. This TIMER variable specifies the integration interval.

2) PRINT. The PRINT card is used to specify the variables that will be printed at each specified interval (PRDEL) during the simulation.

3) METHOD TRAPZ. The integration technique is specified by the use of the METHOD card with the appropriate CSMP III integration name. In this case, the selected method is the trapezoidal (TRAPZ) method that uses a fixed integration interval (DELT).

4) END. The END card specifies the end of the program.

The last segment of the program is a list of the input data stored in the two dimensional array WINPUT. It is specified between the lines INPUT and ENDINPUT. This array must match the FORMAT statement of line 58.

The program ends with the lines

```
464.      STOP
465.      ENDJOB
466.      /*END
```

The ENDJOB card must begin in the first column.

## DESCRIPTION OF THE OUTPUT OF THE MODEL

To provide the user with an example of the output of this model, the program described in section IV of this document was executed for a period of three days.

The output of the model consists of two parts:

1) The first part is generated in the DYNAMIC section (paragraph 24), and for each simulated day an output at 8:00 am and 4:00 pm is printed.

The variables printed for each soil layer are: DEPTH, THETA, PPOT, FLUX, NFLUX, and TEMP.

2) The second part of the output is generated with the PRINT card the TERMINAL section. The variables printed for midnight at the end of each day of the simulation period are: JDNUM, XDNUM, DRN, DINF, DEVP, DDRN, CUMWTR, CUMWT1, CUMWT2, CUMWT3, BALANS, CUMRN, CUMDRN, CUMINF, CUMEVP, and FLOW(14).

It should be noted that for a fixed integration method, such as TRAPZ, the integration interval (DELT) necessary for execution of the model may have to be adapted to the input data. Our experience with this model, using TRAPZ, suggests a DELT of 100 seconds for input data with rain, and 200 seconds for input data with no rain. However, the user has a choice of other integration methods and should consult the CSMP III manual for proper use.



WATER AND HEAT BALANCE OF BARE SOIL- NO RUNOFF  
VAN BAVEL - LASCANO 21 MAY 1979  
PROGRAM USED FOR USER'S GUIDE PREPARATION  
CONSERVATION VARIATION#6

JULIAN DAY NUMBER	1. TIME	28800.0 XNUM	1. STIME	8.0000
DEPTH	THEIA	PPOI	FLUX	NET FLUX
1	0.5000E-02	0.3440E 00	-0.2674E-07	-0.6991E-08
2	0.5000E-01	0.3856E 00	-0.1975E-07	-0.1114E-07
3	0.5000E-01	0.3870E 00	-0.8606E-04	-0.9771E-08
4	0.6500E-01	0.3803E 00	0.1165E-03	-0.1445E-07
5	0.9500E-01	0.3890E 00	0.1502E-07	-0.1506E-07
6	0.1300E 00	0.3689E 00	0.3146E-07	-0.2124E-07
7	0.1750E 00	0.3665E 00	0.5272E-07	-0.2070E-07
8	0.2250E 00	0.3770E 00	0.7341E-07	-0.1768E-07
9	0.3000E 00	0.3849E 00	0.9109E-07	-0.6929E-07
10	0.4000E 00	0.3875E 00	0.1604E-01	-0.6333E-07
11	0.5250E 00	0.3375E 00	0.2238E-03	-0.8779E-07
12	0.7500E 00	0.4021E 00	0.3116E-04	-0.2014E-06
13	0.1050E 01	0.4092E 00	0.5131E-03	-0.1443E-06
				TEMP
				0.3438E 01
				0.3494E 01
				0.3633E 01
				0.4489E 01
				0.5506E 01
				0.6776E 01
				0.8319E 01
				0.9744E 01
				0.1141E 02
				0.1254E 02
				0.1328E 02
				0.1418E 02
				0.1522E 02

JULIAN DAY NUMBER	1. TIME	57600.0 XNUM	1. STIME	16.0000
DEPTH	THEIA	PPOI	FLUX	NET FLUX
1	0.5000E-02	0.3442E 00	-0.6555E-07	-0.3351E-08
2	0.5000E-01	0.3544E 00	-0.6240E-07	-0.2117E-07
3	0.6000E-01	0.3664E 00	-0.4143E-07	-0.1195E-07
4	0.6500E-01	0.3729E 00	-0.5441E 00	-0.1790E-07
5	0.9500E-01	0.3771E 00	-0.1159E-07	-0.1255E-07
6	0.1300E 00	0.3700E 00	0.9670E-07	-0.1293E-07
7	0.1750E 00	0.3770E 00	0.1390E-07	-0.1468E-07
8	0.2250E 00	0.3803E 00	0.2858E-07	-0.8351E-08
9	0.3000E 00	0.3875E 00	0.3693E-07	-0.3501E-07
10	0.4000E 00	0.3731E 00	0.7594E-07	-0.3838E-07
11	0.5250E 00	0.3781E 00	0.1143E-04	-0.5628E-07
12	0.7500E 00	0.3683E 00	0.1766E-04	-0.1213E-06
13	0.1050E 01	0.3647E 00	0.2919E-03	-0.1205E-06
				TEMP
				0.1050E 02
				0.1064E 02
				0.1065E 02
				0.1053E 02
				0.1032E 02
				0.1010E 02
				0.1001E 02
				0.1021E 02
				0.1084E 02
				0.1195E 02
				0.1313E 02
				0.1439E 02
				0.1533E 02

JULIAN DAY NUMBER	2. TIME	115200.0 XNUM	2. STIME	8.0000
DEPTH	THEIA	PPOI	FLUX	NET FLUX
1	0.5000E-02	0.3442E 00	-0.2437E-07	-0.6335E-08
2	0.5000E-01	0.3474E 00	-0.1603E-07	-0.4168E-08
3	0.6000E-01	0.3501E 00	-0.1347E-07	-0.3004E-08
4	0.6500E-01	0.3579E 00	-0.1086E-07	-0.4150E-08
5	0.9500E-01	0.3622E 00	-0.8333E 00	-0.4102E-08
6	0.1300E 00	0.3644E 00	-0.2612E-03	-6.5298E-08
7	0.1750E 00	0.3670E 00	0.2686E-03	-6.6101E-08
8	0.2250E 00	0.3609E 00	0.8787E-04	-0.5508E-08
9	0.3000E 00	0.3508E 00	0.1387E-07	-0.2478E-07
10	0.4000E 00	0.3505E 00	0.3865E-07	-0.2420E-07
11	0.5250E 00	0.3624E 00	0.6285E-07	-0.3324E-07
12	0.7500E 00	0.3709E 00	0.9608E-07	-0.6616E-07
13	0.1050E 01	0.3749E 00	0.1622E-04	-0.7512E-07
				TEMP
				0.3055E 01
				0.2982E 01
				0.3159E 01
				0.3626E 01
				0.4451E 01
				0.5541E 01
				0.6938E 01
				0.8304E 01
				0.1003E 02
				0.1155E 02
				0.1284E 02
				0.1436E 02
				0.1528E 02

JULIAN DAY NUMBER =	2. TIME =	14000.0 XDNUM =	2. STIME = 16.0000	TEMP
DEPTH	THETA	PPOI	FLUX	NET FLUX
1	0.500E-02	0.0	0.4373E-06	-0.3518E-06
2	0.200E-01	-0.9666E-02	0.7891E-06	0.5392E-06
3	0.400E-01	0.0	0.2495E-06	-0.5732E-06
4	0.650E-01	-0.1945E-01	0.8232E-06	0.3111E-06
5	0.950E-01	-0.2520E-01	0.5121E-06	-0.8485E-07
6	0.130E 00	-0.4456E-01	0.5970E-06	0.1728E-07
7	0.175E 00	-0.9563E-01	0.5797E-06	0.6392E-08
8	0.225E 00	-0.3019E 00	0.5733E-06	0.1675E-07
9	0.300E 00	-0.466E 00	0.5565E-06	0.1186E-06
10	0.400E 00	-0.5633E 00	0.4380E-06	0.1434E-06
11	0.5250E 00	-0.6464E 00	0.2946E-06	0.1223E 02
12	0.750E 00	-0.624E 00	0.1531E-06	0.7117E-08
13	0.1050E 01	-0.5649E 00	0.1466E-06	-0.4681E-07

JULIAN DAY NUMBER =	3. TIME =	201600.0 XDNUM =	3. STIME = 8.0000	TEMP
DEPTH	THETA	PPOI	FLUX	NET FLUX
1	0.500E-02	-0.5367E 00	-0.2342E-07	-0.7506E-08
2	0.200E-01	-0.407E 00	-0.1591E-07	-0.8970E-08
3	0.400E-01	-0.4494E 00	-0.6944E-08	-0.5744E-08
4	0.650E-01	-0.420E 00	-0.1191E-08	-0.6248E-08
5	0.950E-01	-0.408E 00	-0.5031E-08	-0.5835E-08
6	0.130E 00	-0.4167E 00	-0.1084E-07	-0.9263E-08
7	0.175E 00	-0.4467E 00	-0.2011E-07	-0.1368E-07
8	0.225E 00	-0.7517E 00	-0.3381E-07	-0.7445E-08
9	0.300E 00	-0.7081E 00	-0.4124E-07	-0.3533E-07
10	0.400E 00	-0.6579E 00	-0.7661E-07	-0.3158E-07
11	0.5250E 00	-0.6125E 00	-0.1081E-06	-0.3926E-07
12	0.750E 00	-0.5049E 00	-0.1471E-06	-0.4222E-07
13	0.1050E 01	-0.5560E 00	-0.1897E-06	-0.8329E-08

JULIAN DAY NUMBER =	3. TIME =	230400.0 XDNUM =	3. STIME = 16.0000	TEMP
DEPTH	THETA	PPOI	FLUX	NET FLUX
1	0.500E-02	-0.2955E 01	-0.6327E-07	-0.8777E-08
2	0.200E-01	-0.1587E 01	-0.5450E-07	-0.1356E-07
3	0.400E-01	-0.902E 00	-0.4094E-07	-0.1613E-07
4	0.650E-01	-0.6643E 00	-0.2481E-07	-0.1281E-07
5	0.950E-01	-0.5308E 00	-0.1200E-07	-0.1281E-07
6	0.130E 00	-0.550E 00	-0.8108E-06	-0.1173E-07
7	0.175E 00	-0.6068E 00	-0.1254E-07	-0.9526E-08
8	0.2250E 00	-0.1585E 00	-0.2206E-07	-0.5467E-08
9	0.300E 00	-0.6105E 00	-0.2753E-07	-0.2550E-07
10	0.400E 00	-0.7538E 00	-0.5363E-07	-0.2424E-07
11	0.5250E 00	-0.6963E 00	-0.7727E-07	-0.3175E-07
12	0.750E 00	-0.6198E 00	-0.1050E-06	-0.4697E-07
13	0.1050E 01	-0.5811E 00	-0.1560E-06	-0.2903E-07

TIME	0.0	86400.	1.72800E 05	2.59200E 05
JDAUM	1.0000	2.0000	3.0000	4.0000
XDAUM	1.0000	2.0000	3.0000	4.0000
CRN	0.0	0.0	2.49998E-02	0.0
DIAF	0.0	0.0	2.50310E-02	0.0
DEVP	0.0	3.51304E-03	3.26261E-03	3.23833E-03
DDEN	0.0	5.29276E-02	1.92041E-02	1.53041E-02
CUM*TR	0.50400	0.44750	0.44999	0.43036
CUM*TI	0.45780	0.40811	0.40735	0.39167
CUM*TI	0.39900	0.35664	0.35391	0.34091
CUM*TI	0.25200	0.22894	0.22291	0.21843
BALANS	0.0	-0.09830E-05	-1.38283E-04	-2.18668E-04
CUMRN	0.0	0.0	2.49998E-02	2.49998E-02
CUMRN	0.0	5.29276E-02	7.21317E-02	8.04358E-02
CUMINE	0.0	0.0	2.50310E-02	2.50310E-02
CUMIEP	0.0	3.51304E-03	6.77565E-03	1.00140E-02
FLOW(14)	5.91804E-05	1.1068	-2.4480	-5.5339

## REFERENCES

1. Brunt, D. 1932. Notes on radiation in the atmosphere. Quarterly J. of Royal Met. Society. 58:380-420.
2. De Vries, D.A. 1966. Thermal properties of soils. In: Van Wijk (Ed), Physics of Plant Environment, 2nd edition, pp 210-235. N. Holland Publ. Co.
3. Forsythe, W.E. 1964. Smithsonian Physical Tables. Smithsonian Institution. Publication 4169. 827pp.
4. Hillel, D.I., C.H.M. van Bavel, and H. Talpaz. 1975. Dynamic simulation of water storage in fallow soil as affected by mulch of hydrophobic aggregates. Soil Sci. Soc. Amer. Proc. 39:826-833.
5. Horton, Robert. 1977. Field test of hydrophobic soil clod mulch for soil water conservation in a semiarid area. M.S. Thesis, Texas A&M University, 114pp.
6. Humphreys, K.B. 1979. Comparison of methods for determining soil hydraulic characteristics. M.S. Thesis, Texas A&M University, 91pp.
7. IBM Corporation. 1975. Continuous System Modeling Program III (CSMP III). Program Reference Manual. SH19-7001-3. Data Processing Division, 112 East Post Road, White Plains, New York 10601, 205pp.
8. Jackson, R.D. 1972. On the calculation of hydraulic conductivity. Soil Sci. Soc. Amer. Proc. 36:380-382.
9. Marek, T.H. 1977. Hydraulic characteristics of short, blocked irrigation furrows. M.S. Thesis, Texas A&M University, 135pp.
10. Murray, F.W. 1967. On the computation of saturation vapor pressure. J. of Appl. Met. 6:203-205.
11. Saffaf, A.Y. 1966. Field determination of hydraulic conductivity of Norwood silt loam. M.S. Thesis, Texas A&M University, 111pp.
12. Sellers, W.D. 1965. Physical Climatology. U. of Chicago Press. 272pp.
13. Van Bavel, C.H.M., and D.I. Hillel. 1975. A simulation study of soil heat and moisture dynamics as affected by a dry mulch. Proc. 1975 Summer Computer Simulation Conf., pp815-821, San Francisco, Cal. Simulation Councils, Inc., La Jolla, Cal.

14. Van Bavel, C.H.M., and D.I. Hillel. 1976. Calculating potential and actual evaporation from a bare soil surface by simulation of concurrent flow of water and heat. Agric. Metereol. 17:453-476.

## APPENDICES

## APPENDIX A - GLOSSARY OF VARIABLE NAMES

TITLE: GLOSSARY FOR HEAT AND WATER BALANCE MODEL

NO.....	TERM.....	DEFINITION.....	UNITS
1.	A.....	SENSIBLE HEAT FLUX INTO THE AIR.....	W/M**2
2.	ALB.....	ALBEDO.....	-
3.	AVCOND(I) ..	AVERAGE HYDRAULIC CONDUCTIVITY.....	
		..BETWEEN ADJACENT LAYERS.....	M/S
4.	AVKOND(I) ..	AVERAGE THERMAL CONDUCTIVITY.....	
		..BETWEEN ADJACENT LAYERS.....	W/(M*C)
5.	BALANS.....	WATER BALANCE.....	M
5.	BEGIN.....	BEGINNING OF RAINFALL PERIOD.....	HOURS
7.	COND(I).....	HYDRAULIC CONDUCTIVITY OF LAYER (I) ..	M/S
8.	CUMDRN.....	CUMULATIVE DRAINAGE.....	M
9.	CUM EVP.....	CUMULATIVE EVAPORATION.....	M
10.	CUMINF.....	CUMULATIVE INFILTRATION.....	M
11.	CUMRN.....	CUMULATIVE RAIN.....	M
12.	CUMWTR.....	TOTAL WATER IN SOIL PROFILE.....	M
13.	CUMWT1.....	TOTAL WATER (I=6,NL).....	M
14.	CUMWT2.....	TOTAL WATER (I=9,NL).....	M
15.	CUMWT3.....	TOTAL WATER (I=12,NL) ..	M
16.	DDRN.....	DAILY DRAINAGE.....	M
17.	DEPTH(I) ..	VERTICAL DISTANCE BETWEEN MIDPOINT..	
		..OF LAYER (I) AND THE SURFACE.....	M
18.	DETAIN.....	DEPTH OF WATER ON THE SOIL SURFACE..	M
19.	DEVAP.....	DAILY EVAPORATION.....	M
20.	DINF.....	DAILY INFILTRATION.....	M
21.	DIST(I).....	DISTANCE BETWEEN MIDPOINTS OF .....	
		....ADJACENT SOIL LAYERS (I,I+1) .....	M
22.	DL.....	DAY LENGTH .....	HOURS
23.	DNUM.....	DAY COUNTER.....	-
24.	DNUM1.....	DAY COUNTER.....	-
25.	DNUM2.....	DAY COUNTER.....	-
26.	DPMAX.....	DEWPOINT TEMP. AT TIME OF TMAX.....	C
27.	DPMIN.....	DEWPOINT TEMP. AT TIME OF TMIN.....	C
28.	DPTC.....	DEWPOINT TEMPERATURE.....	C
29.	DRAIN.....	DRAINAGE.....	M/S
30.	DRN.....	DAILY RAIN.....	M
31.	DWSLOP.....	RAINFALL SLOPE BETWEEN MIDPOINT AND.	
		.....END.....	MM/HR**2
32.	END.....	END OF RAINFALL PERIOD.....	HOURS
33.	EV.....	EVAPORATION (DUMMY VARIABLE).....	M/S
34.	EVAP.....	EVAPORATION.....	M/S
35.	EVP.....	EVAPORATION (DUMMY VARIABLE).....	M/S
36.	FLOW(I).....	FLOW OF HEAT INTO LAYER (I) .....	W/M**2
37.	FLOW(NLL) ..	FLOW OF HEAT ACROSS THE LOWER.....	
		..BOUNDARY.....	W/M**2
38.	FLUX(I).....	FLUX OF WATER INTO LAYER (I) .....	M/S
39.	FLUX(NLL) ..	FLUX OF WATER ACROSS THE LOWER.....	



..BOUNDARY.....M/S  
 40. FTSC.....FINAL TEMPERATURE OF SOIL SURFACE...  
       .....AS CALCULATED IN THE IMPLICIT LOOP..C  
  
 41. GR.....GLOBAL RADIATION.....W/M\*\*2  
  
 42. HA.....ABSOLUTE HUMIDITY OF THE AIR.....KG/M\*\*3  
 43. HEIGHT.....RAINFALL RATE AT MIDPOINT.....MM/HOUR  
 44. HO.....SATURATED HUMIDITY AT THE SOIL.....  
       .....SURFACE AND ABSOLUTE HUMIDITY.....KG/M\*\*3  
 45. HPOT(I)....HYDRAULIC POTENTIAL OF SOIL LAYER...M OF WATER  
 46. HS.....ABSOLUTE HUMIDITY.....KG/M\*\*3  
 47. HSO.....ABSOLUTE HUMIDITY, DUMMY VARIABLE...KG/M\*\*3  
 48. HTIME.....TIME.....HOURS  
  
 49. INCAP.....INFILTRATION CAPACITY.....M/S  
 50. INF.....INFILTRATION.....M  
 51. INFILT.....INFILTRATION RATE.....M/S  
 52. ITEMP(I)...INITIAL TEMPERATURE OF LAYER (I)....C  
 53. IPHETA(I)..INITIAL VOLUMETRIC WATER CONTENT....  
       ..OF LAYER (I).....M\*\*3/M\*\*3  
 54. IVHCAP(I)..INITIAL VOLUMETRIC HEAT CAPACITY....  
       ..OF LAYER (I).....J/(M\*\*3\*C)  
 55. IVOLH(I)...INITIAL AMOUNT OF HEAT IN LAYER (I).J/M\*\*2  
 56. IVOLW(I)...INITIAL VOLUME OF WATER IN .....  
       ...LAYER (I).....M  
 57. IWATER.....INITIAL TOTAL WATER CONTENT OF.....  
       .....THE SOIL PROFILE.....M  
  
 58. JDNUM.....JULIAN DAY NUMBER..... -  
  
 59. KOND(I)....THERMAL CONDUCTIVITY OF LAYER (I)...W/(M\*C)  
 60. KONDA.....THERMAL CONDUCTIVITY OF AIR.....W/(M\*C)  
 61. KONDS.....THERMAL CONDUCTIVITY OF SOIL.....W/(M\*C)  
 62. KONDV.....THERMAL CONDUCTIVITY BY WATER VAPOR.W/(M\*C)  
 63. KONDW.....THERMAL CONDUCTIVITY BY WATER.....W/(M\*C)  
  
 64. LH.....LATENT HEAT OF VAP. OF WATER.....J/M\*\*3  
  
 65. MDPNT.....MIDPOINT OF RAINFALL PERIOD.....HOURS  
  
 66. NFLOW(I)...NET FLOW OF HEAT INTO LAYER (I).....W/M\*\*2  
 67. NPLUX(I)...NET FLUX OF WATER INTO LAYER (I)....M/S  
 68. NL.....NUMBER OF LAYERS..... -  
 69. NLL.....NL + 1..... -  
 70. NR.....NET RADIATION AT THE SOIL SURFACE...W/M\*\*2  
  
 71. PORSTY.....POROSITY OF THE SOIL..... -  
 72. PPOT(I)....PRESSURE POTENTIAL OF LAYER (I).....M OF WATER  
  
 73. RA.....BOUNDARY LAYER RESISTANCE.....S/M

74. RAIN.....RAINFALL RATE.....M/S  
 75. RFT.....TOTAL RAINFALL BETWEEN BEGIN AND ...  
       .....END.....MM  
 76. RHS.....RELATIVE HUMIDITY OF THE SOIL SURFACE -  
 78. RN.....RAIN (DUMMY VARIABLE).....M  
  
 78. S.....CONDUCTION OF ENERGY INTO THE SOIL..  
       .....SURFACE.....W/M\*\*2  
 79. SA.....WINDSPEED.....M/S  
 80. SATCON.....SATURATED HYDRAULIC CONDUCTIVITY OF.  
       .....THE SURFACE HORIZON.....M/S  
 81. SH.....VOLUMETRIC HEAT CAPACITY OF THE AIR..J/(M\*\*3\*C)  
 82. SIGMA.....STEFAN-BOLTZMAN CONSTANT.....W/(M\*\*2\*K\*\*4)  
 83. SKL.....SKY RADIANCE.....W/M\*\*2  
 84. STIME.....TIME.....HOURS  
  
 85. T1.....WATER CONTENT OF FIRST LAYER.....  
       .....(DUMMY VARIABLE).....M\*\*3/M\*\*3  
 86. TAC.....TEMPERATURE OF THE AIR.....C  
 87. TAK.....TEMPERATURE OF THE AIR.....K  
 88. TAMAX.....MAXIMUM AIR TEMPERATURE.....C  
 89. TAMIN.....MINIMUM AIR TEMPERATURE.....C  
 90. TCOM(I).....THICKNESS OF LAYER (I).....M  
 91. TEMP(I).....TEMPERATURE OF LAYER(I).....C  
 92. TEVSKO.....SOIL TEMPERATURE VS. THERMAL.....  
       .....CONDUCTIVITY BY WATER VAPOR.....C VS. W/(M\*C)  
 93. THETA(I).....VOLUMETRIC WATER CONTENT OF LAYER...  
       .....(I).....M\*\*3/M\*\*3  
 94. T1VSAL.....VOLUMETRIC WATER CONTENT OF FIRST...  
       .....SOIL LAYER VS ALBEDO..... -  
 95. TSC.....TEMPERATURE OF THE SOIL SURFACE.....C  
 96. TVSC1.....VOLUMETRIC WATER CONTENT VS. HYDRAULIC  
       .....CONDUCTIVITY FOR FIRST HORIZON..... -  
 97. TVSC2.....VOLUMETRIC WATER CONTENT VS. HYDRAULIC  
       .....CONDUCTIVITY FOR SECOND HORIZON..... -  
 98. TVSP1.....VOLUMETRIC WATER CONTENT VS. PRESSURE  
       .....POTENTIAL FOR FIRST HORIZON..... -  
 99. TVSP2.....VOLUMETRIC WATER CONTENT VS. PRESSURE  
       .....POTENTIAL FOR SECOND HORIZON..... -  
  
 100. UPSLOP.....RAINFALL SLOPE BETWEEN BEGIN AND .....  
       .....MIDPOINT.....MM/HR\*\*2  
  
 101. VHCAP(I).....VOLUMETRIC HEAT CAPACITY OF LAYER (I)..J/(M\*\*3\*C)  
 102. VHCAPS.....VOLUMETRIC HEAT CAPACITY OF THE SOIL..J/(M\*\*3\*C)  
 103. VHCAPW.....VOLUMETRIC HEAT CAPACITY OF WATER.....J/(M\*\*3\*C)  
 104. VOLH(I).....VOLUMETRIC HEAT CONTENT OF LAYER (I)..J/M\*\*2  
 105. VOLW(I).....VOLUME OF WATER PER UNIT AREA OF LAYER  
       .....(I).....M\*\*3/M\*\*2  
  
 106. WINPUT.....ARRAY FOR WEATHER INPUT DATA..... -  
  
 107. ZO.....SURFACE ROUGHNESS COEFFICIENT..... -

## APPENDIX B - PROGRAM LISTING

```

1.      **** A.....JOB CONTROL LANGUAGE
2.      ****
3.      ****
4.      //SCSDRYJA JOB (R042,403A,003,020,RL), ' VAN BAVEL - LASCANO'
5.      /*LEVEL      0
6.      /*JOBPARM R=128
7.      // EXEC CSMP3CLG
8.      //COMPRINT DD DUMMY
9.      //SYSPRINT DD DUMMY
10.     //SYSIN DD *
11.     ****
12.     ****
13.     **** B.....TITLE, MEMORY ORGANIZATION AND ALLOCATION
14.     ****
15.     ****
16.     TITLE          WATER AND HEAT BALANCE OF BARE SOIL- NO RUNOFF
17.     TITLE          VAN BAVEL - LASCANO  21 MAY 1979
18.     TITLE          PROGRAM USED FOR USER'S GUIDE PREPARATION
19.     TITLE          CONSERVB VARIATION#6
20.     ****
21.     STORAGE        TCOM(25),ITHETA(25),DEPTH(25),COND(25),HPOT(25)
22.     STORAGE        AVCOND(25),FLUX(25),PPOT(25),DIST(25)
23.     STORAGE        AVKOND(25),FLOW(25),KOND(25),TEMP(25),VHCAP(25),IVHCAP(25)
24.     /      DIMENSION VOLW(25),IVOLW(25),NFLUX(25),THETA(25)
25.     /      DIMENSION TEMP(25),IVOLH(25),VOLH(25),NFLOW(25)
26.     /      DIMENSION WINPUT(11,37)
27.     /      DIMENSION INF(38),RN(38),EVP(38),DRAIN(38)
28.     /      EQUIVALENCE (VOLW1,VOLW(1)),(IVOLW1,IVOLW(1)),(NFLUX1,NFLUX(1))
29.     /      EQUIVALENCE (VOLH1,VOLH(1)),(IVOLH1,IVOLH(1)),(NFLOW1,NFLOW(1))
30.     FIXED          I..J,K,N1,N11,DNUM,DNUM1,DNUM2
31.     *****
32.     ****
33.     **** C.....INITIAL SECTION
34.     ****
35.     ****
36.     INITIAL
37.     *****
38.     NOSORT
39.     **** 1) DEFINITION OF PARAMETERS
40.     PARAMETER      NL=13
41.     NLL= NL + 1
42.     PARAMETER      KONDS = 4.2
43.     PARAMETER      KONDW = 0.57
44.     PARAMETER      KONDA = 0.025
45.     PARAMETER      VHCAPS= 1.925E06
46.     PARAMETER      VHCAPW= 4.186E06
47.     PARAMETER      SIGMA = 5.67E-08
48.     PARAMETER      Z0    = 0.01
49.     PARAMETER      SATCON= 0.50E-06
50.     PARAMETER      PORSTY= 0.42
51.     **** 2) DAILY COUNTERS
52.     DNUM = 1
53.     DNUM1= 2
54.     DNUM2= 3
55.     **** 3) READ INPUT DATA
56.     DO 10 K=1,37
57.     READ(5,1000)(WINPUT(J,K),J=1,11)
58.     1000 FORMAT(F5.0,1X,F5.2,9(1X,F4.1))
59.     IF(WINPUT(1,K).EQ.0.0) GO TO 11
60.     10 CONTINUE

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```

61.      11 CONTINUE
62.      **** 4) SPECIFICATION OF THE GEOMETRY OF THE SYSTEM,
63.      **** INITIAL WATER CONTENT AND TEMPERATURE
64.      TABLE      TCOM(1-13)=0.01,0.02,0.02,0.03,0.03,0.04,0.05,0.05,...
65.                      0.10,0.10,0.15,0.30,0.30
66.      TABLE      ITHETA(1-13)=13*0.42
67.      TABLE      ITEMP(1-13)=3.57,4.92,6.52,8.17,9.66,10.84,11.69,...
68.                      12.08,12.18,12.26,12.69,13.81,15.22
69.      **** 5) CALCULATION OF DISTANCE AND DEPTH
70.          DEPTH(1) = 0.5*TCOM(1)
71.          DIST(1) = DEPTH(1)
72.          DO 20 I=2,NL
73.              DIST(I) = 0.5*(TCOM(I-1)+TCOM(I))
74.              DEPTH(I) = DEPTH(I-1) + 0.5*(TCOM(I-1)+TCOM(I))
75.      20 CONTINUE
76.      **** 6) CALCULATION OF INITIAL WATER AND TEMPERATURE CONDITIONS
77.      **** FLUX REFERS TO WATER
78.      **** FLOW REFERS TO HEAT
79.          IWATER = 0.0
80.          DO 30 I=1,NL
81.              IVHCAP(I) = VHCAPW*ITHETA(I)+(1.0-PORSTY)*VHCAPS
82.              IWATER = IWATER + TCOM(I)*ITHETA(I)
83.              IVOLH(I) = ITEMP(I)*TCOM(I)*IVHCAP(I)
84.              NFLUX(I) = 0.0
85.              NFLOW(I) = 0.0
86.              IVOLW(I) = ITHETA(I)*TCOM(I)
87.      30 CONTINUE
88.      ****
89.      ****
90.      **** HYDRAULIC CHARACTERISTICS OF FIRST HORIZON 0.0-0.20 M
91.      **** VOLUMETRIC WATER CONTENT VS. PRESSURE POTENTIAL
92.      **** IN M WATER COLUMN
93.      FUNCTION TVSP1 = ( 0.030, -29000.00), ...
94.                      ( 0.050, -16000.00), ...
95.                      ( 0.070, -10000.00), ...
96.                      ( 0.090, -6000.00), ...
97.                      ( 0.110, -3000.00), ...
98.                      ( 0.130, -1500.00), ...
99.                      ( 0.150, -700.00), ...
100.                     ( 0.170, -370.00), ...
101.                     ( 0.190, -160.00), ...
102.                     ( 0.210, -74.00), ...
103.                     ( 0.230, -45.00), ...
104.                     ( 0.250, -30.00), ...
105.                     ( 0.270, -18.00), ...
106.                     ( 0.290, -11.00), ...
107.                     ( 0.310, -7.20), ...
108.                     ( 0.330, -3.60), ...
109.                     ( 0.350, -1.20), ...
110.                     ( 0.370, -0.60), ...
111.                     ( 0.390, -0.22), ...
112.                     ( 0.410, -0.07), ...
113.                     ( 0.420, 0.00), ...
114.                     ( 1.000, 0.00)
115.      **** VOLUMETRIC WATER CONTENT VS. HYDRAULIC CONDUCTIVITY IN M/S
116.      FUNCTION TVSC1 = ( 0.040, 0.1980432E-18), ...
117.                      ( 0.060, 0.1867095E-17), ...
118.                      ( 0.080, 0.9215115E-17), ...
119.                      ( 0.100, 0.3565605E-16), ...
120.                      ( 0.120, 0.1411493E-15), ...
121.                      ( 0.140, 0.6032844E-15), ...

```

122.	( 0.160, 0.2846457E-14), ...
123.	( 0.180, 0.1263317E-13), ...
124.	( 0.200, 0.6312881E-13), ...
125.	( 0.220, 0.3265092E-12), ...
126.	( 0.240, 0.1312614E-11), ...
127.	( 0.260, 0.4195633E-11), ...
128.	( 0.280, 0.1239914E-10), ...
129.	( 0.300, 0.3590753E-10), ...
130.	( 0.320, 0.9914647E-10), ...
131.	( 0.340, 0.3065372E-09), ...
132.	( 0.360, 0.1694214E-08), ...
133.	( 0.380, 0.8728055E-08), ...
134.	( 0.400, 0.5553067E-07), ...
135.	( 0.420, 0.5000000E-06), ...
136.	( 1.000, 0.5000000E-06)
137.	**** HYDRAULIC CHARACTERISTICS OF SECOND HORIZON 0.20-1.20 M
138.	**** VOLUMETRIC WATER CONTENT VS. PRESSURE POTENTIAL
139.	FUNCTION TVSP2 = ( 0.020, -760.00), ...
140.	( 0.040, -340.00), ...
141.	( 0.060, -130.00), ...
142.	( 0.080, -60.00), ...
143.	( 0.100, -24.00), ...
144.	( 0.120, -15.00), ...
145.	( 0.140, -10.00), ...
146.	( 0.160, -7.40), ...
147.	( 0.180, -5.40), ...
148.	( 0.200, -4.40), ...
149.	( 0.220, -3.40), ...
150.	( 0.240, -2.80), ...
151.	( 0.260, -2.30), ...
152.	( 0.280, -1.90), ...
153.	( 0.300, -1.50), ...
154.	( 0.320, -1.20), ...
155.	( 0.340, -0.94), ...
156.	( 0.360, -0.70), ...
157.	( 0.380, -0.45), ...
158.	( 0.400, -0.27), ...
159.	( 0.420, -0.15), ...
160.	( 0.440, -0.06), ...
161.	( 0.450, 0.00), ...
162.	( 1.000, 0.00)
163.	**** VOLUMETRIC WATER CONTENT VS. HYDRAULIC CONDUCTIVITY
164.	FUNCTION TVSC2 = ( 0.030, 0.1200167E-14), ...
165.	( 0.050, 0.1599529E-13), ...
166.	( 0.070, 0.1516890E-12), ...
167.	( 0.090, 0.1062001E-11), ...
168.	( 0.110, 0.7476516E-11), ...
169.	( 0.130, 0.3470373E-10), ...
170.	( 0.150, 0.1199559E-09), ...
171.	( 0.170, 0.3375351E-09), ...
172.	( 0.190, 0.8332817E-09), ...
173.	( 0.210, 0.1842094E-08), ...
174.	( 0.230, 0.3760615E-08), ...
175.	( 0.250, 0.7218816E-08), ...
176.	( 0.270, 0.1315320E-07), ...
177.	( 0.290, 0.2300420E-07), ...
178.	( 0.310, 0.3924749E-07), ...
179.	( 0.330, 0.6606643E-07), ...
180.	( 0.350, 0.1105985E-06), ...
181.	( 0.370, 0.1868858E-06), ...
182.	( 0.390, 0.3336319E-06), ...

```

183.          ( 0.410, 0.6711355E-06), ...
184.          ( 0.430, 0.1617800E-05), ...
185.          ( 0.450, 0.6000000E-05), ...
186.          ( 1.000, 0.6000000E-05)
187.  ****      SOIL TEMPERATURE VS. HEAT CONDUCTIVITY BY VAPOR IN W/(M*C)
188.  FUNCTION TEVSKO = ( -1.000, 0.02000), ...
189.                  ( 0.000, 0.02470), ...
190.                  ( 10.000, 0.04190), ...
191.                  ( 20.000, 0.07990), ...
192.                  ( 30.000, 0.12600), ...
193.                  ( 40.000, 0.24700), ...
194.                  ( 50.000, 0.38100), ...
195.                  ( 60.000, 0.65000), ...
196.                  ( 70.000, 1.17000)
197.  ****      VOLUMETRIC WATER CONTENT OF FIRST LAYER VS. ALBEDO
198.  FUNCTION TIVSAL = ( 0.00, 0.22), ...
199.                  ( 0.10, 0.22), ...
200.                  ( 0.25, 0.17), ...
201.                  ( 1.00, 0.17)
202.  ****
203.  ****
204.  ****  7)  TABLE OF THE GEOMETRY OF THE SYSTEM AND ITS INITIAL STATE
205.  ****
206.          WRITE(6,1100)
207.          1100 FORMAT('0 I      TCOM      DEPTH      ITHETA      ITEMP')
208.          DO 40 I=1,NLL
209.              40 WRITE(6,1200) I,TCOM(I),DEPTH(I),ITHETA(I),ITEMP(I)
210.              1200 FORMAT(1H ,I2,4F10.5)
211.  ****
212.  ****
213.  ****  D.....DYNAMIC SECTION
214.  ****
215.  ****
216.  DYNAMIC
217.  ****
218.  NOSORT
219.  ****
220.  ****  1)  DEFINITION OF TIME RELATED VARIABLES
221.          HTIME=TIME/3600.
222.          STIME=AMOD(HTIME,24.)
223.          Y=IMPULS(86400.,86400.)
224.          IF(Y.LT.0.5) GO TO 22
225.          DNUM = DNUM + 1
226.          DNUM1 = DNUM1 + 1
227.          DNUM2 = DNUM2 + 2
228.          22 CONTINUE
229.          XDNUM=FLOAT(DNUM)
230.          JDNUM = WINPUT (1,DNUM)
231.  ****  2)  CALCULATION OF HYDRAULIC CHARACTERISTICS OF FIRST HORIZON
232.          DO 50 I=1,8
233.              THETA(I) = VOLW(I)/TCOM(I)
234.              COND(I)=AFGEN( TVSC1,THETA(I))
235.              PPOT(I)=AFGEN( TVSP1,THETA(I))
236.              HPOT(I)=PPOT(I)-DEPTH(I)
237.          50 CONTINUE
238.  ****  3)  CALCULATION OF HYDRAULIC CHARACTERISTICS OF SECOND HORIZON
239.          DO 60 I=9,NL
240.              THETA(I) = VOLW(I)/TCOM(I)
241.              COND(I)=AFGEN( TVSC2,THETA(I))
242.              PPOT(I)=AFGEN( TVSP2,THETA(I))
243.              HPOT(I)=PPOT(I)-DEPTH(I)

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244.      60 CONTINUE
245.      **** 4) CALCULATION OF THERMAL PROPERTIES
246.          DO 70 I=1,NL
247.              VHCAP(I) = VHCAPW*THETA(I) + (1.0 - PORSTY)*VHCAPS
248.              TEMP(I) = VOLH(I)/(VHCAP(I)*TCOM(I))
249.              KONDV = AFGEN (TEVSKO,TEMP(I))
250.              KOND(I) = ((1. -PORSTY)*KONDS*0.4 + THETA(I)*KONDW + ...
251.                  (PORSTY - THETA(I))*1.4*(KONDA + KONDV))/ ...
252.                  ((1.-PORSTY)*.4+THETA(I)+(PORSTY-THETA(I))*1.4)
253.          70 CONTINUE
254.      **** 5) CALCULATION OF AVERAGE CONDUCTIVITIES
255.          DO 80 I = 2,NL
256.              AVKOND(I) = (TCOM(I-1)+TCOM(I))/(TCOM(I-1)/KOND(I-1) ...
257.                  + TCOM(I)/KOND(I))
258.              AVCOND(I)=(COND(I-1)*TCOM(I-1)+COND(I)*TCOM(I))/...
259.                  (TCOM(I-1)+TCOM(I))
260.      80 CONTINUE
261.      **** 6) SPECIFICATION OF BOUNDARY CONDITIONS FOR FLOW OF HEAT
262.      **** AND FLUX OF WATER
263.          FLUX(NLL)= COND(NL)
264.          FLOW(NLL)=(TEMP(NL)-ITEMP(NL))*KOND(NL)/(TCOM(NL)/2.)
265.      **** 7) CALCULATION OF FLOW OF HEAT AND FLUX OF WATER
266.          DO 90 I = 2,NL
267.              FLOW(I) = (TEMP(I-1) - TEMP(I))*AVKOND(I)/DIST(I)
268.              FLUX(I)=(HPOT(I-1)-HPOT(I))*AVCOND(I)/DIST(I)
269.      90 CONTINUE
270.      **** 8) USE DAILY RAINFALL DATA, AND CALCULATE DAILY
271.      **** RAINFALL DISTRIBUTION
272.          BEGIN = WINPUT(9,DNUM)
273.          END = WINPUT(10,DNUM)
274.          RFT = WINPUT(11,DNUM)
275.          RAIN=0.0
276.          IF(RFT.EQ.0.0) GO TO 33
277.          UPSLOP=(4.0*RFT)/((END-BEGIN)**2)
278.          DWSLOP=-UPSLOP
279.          MDPNT=(BEGIN+END)/2.0
280.          HEIGHT=(2.0*RFT)/(END-BEGIN)
281.          IF(STIME.GE.BEGIN.AND.STIME.LE.MDPNT)RAIN=...
282.              (UPSLOP*(STIME-BEGIN))/3600000.0
283.          IF(STIME.GT.MDPNT.AND.STIME.LE.END)RAIN=...
284.              (DWSLOP*(STIME-END))/3600000.0
285.      33 CONTINUE
286.      **** 9) USE DAY LENGTH AND CALCULATE DAILY DISTRIBUTION OF
287.      **** GLOBAL RADIATION
288.          DL=WINPUT(2,DNUM)
289.      **** DGR/86400.*1.E06*24./DL*PI/2.=436.33*DGR/DL
290.          GR=436.33*WINPUT(3,DNUM)/DL*SIN((STIME-12.+DL/2.)...
291.              *3.141/DL)
292.          IF (GR.LE.0.0) GR = 0.0
293.      **** 10) CALCULATION OF ALBEDO
294.          T1 = THETA(1)
295.          ALB =AFGEN(T1VSAL,T1)
296.      **** 11) CALCULATION OF WINDSPEED AND BOUNDARY LAYER RESISTANCE
297.          IF(HTIME.LE.12.) SA=WINPUT(8,DNUM)
298.          IF(HTIME.LE.12.) GO TO 44
299.          IF(STIME.LE.12.)SA=WINPUT(8,DNUM-1)+(STIME+12.)/24.* ...
300.              (WINPUT(8,DNUM)-WINPUT(8,DNUM-1))
301.          IF(STIME.LE.12.) GO TO 44
302.          SA=WINPUT(8,DNUM)+(STIME-12.)/24.*(WINPUT(8,DNUM+1)-...
303.              WINPUT(8,DNUM))
304.      44 CONTINUE

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305.      RA = (ALOG(2.0/Z0)**2.0)/(0.16*SA)
306.  **** 12)  CALCULATION OF DEWPOINT TEMPERATURE AND ABSOLUTE HUMIDITY
307.      DPMAX=WINPUT(6,DNUM)
308.      DPMIN=WINPUT(7,DNUM)
309.      DPTC=DPMIN+(DPMAX-DPMIN)*(STIME-5.)/10.
310.      IF(STIME.GT.15.)DPMIN=WINPUT(7,DNUM+1)
311.      IF(STIME.GT.15.)DPTC=DPMAX-(DPMAX-DPMIN)*(STIME-15.)/14.
312.      IF(STIME.LT.5.AND.DNUM.GE.2.)DPMAX=WINPUT(6,DNUM-1)
313.      IF(STIME.LT.5.)DPTC=DPMAX-(DPMAX-DPMIN)*(STIME+9.)/14.
314.      HA = 1.323*EXP(17.27*DPTC/(237.3+DPTC))/(273.16+DPTC)
315.  **** 13)  CALCULATION OF TEMPERATURE OF THE AIR AND SH OF THE AIR
316.      TAMAX=WINPUT(4,DNUM)
317.      TAMIN=WINPUT(5,DNUM)
318.      TAC=TAMIN+(TAMAX-TAMIN)*(STIME-5.)/10.
319.      IF(STIME.GT.15.)TAMIN=WINPUT(5,DNUM+1)
320.      IF(STIME.GT.15.)TAC=TAMAX-(TAMAX-TAMIN)*(STIME-15.)/14.
321.      IF(STIME.LT.5.AND.DNUM.GE.2.)TAMAX=WINPUT(4,DNUM-1)
322.      IF(STIME.LT.5.)TAC=TAMAX-(TAMAX-TAMIN)*(STIME+9.)/14.
323.      TAK=TAC+273.16
324.      SH=(1154.8*303.16)/(TAK)
325.  **** 14)  CALCULATION OF SKY IRRADIANCE
326.      SKL=(SIGMA*TAK**4)*(0.605+0.039*SQRT(1410.*HA))
327.  **** 15)  IMPLICIT CALCULATION OF THE SOIL SURFACE TEMPERATURE
328.      TSC = IMPL (TAC,0.01,FTSC)
329.      A = (TSC - TAC)*SH/RA
330.      HO = 1.323*EXP(17.27*TSC / (237.3+TSC ))/(273.16+TSC )
331.      HO=HO*EXP(PPOT(1)/(46.97*(TSC+273.16)))
332.      EV =(HO - HA)/(RA*1000.)
333.      S = GR*(1. - ALB) + SKL - SIGMA*(TSC + 273.16)**4 ...
334.          - A -LH*EV
335.      FTSC = TEMP(1) + S*DEPTH(1)/KOND(1)
336.  **** 16)  CALCULATION OF EVAPORATION AND NET RADIATION
337.      FLOW(1) = (TSC - TEMP(1))*KJND(1)/DIST(1)
338.      HS = 1.323*EXP(17.27*TSC / (237.3+TSC ))/(273.16+TSC )
339.      HSO = HS
340.      HS=HS*EXP(PPOT(1)/(46.97*(TSC+273.16)))
341.      RHS = HS/HSO
342.      EVAP = (HS - HA)/(RA*1000.)
343.      LH=2.49463E09-2.247E06*TSC
344.      NR = FLOW(1) + (TSC - TAC)*SH/RA + LH*EVAP
345.  **** 17)  CALCULATION OF DETAIN, INFILTRATION, AND INCAP
346.      DETAIN = INTGRL (0.0, RAIN-INFILT)
347.      INCAP = (0.-HPOT(1))*0.5*(SATCON+COND(1)) / DIST(1)
348.      IF (RAIN.GT.0.0) GO TO 55
349.      IF (DETAIN.LE.0.0) GO TO 66
350.      INFILT=INCAP
351.      GO TO 77
352.  66 CONTINUE
353.      DETAIN = 0.0
354.      INFILT=0.0
355.      GO TO 77
356.  55 CONTINUE
357.      INFILT = INCAP
358.      IF (RAIN. LT. INCAP. AND. DETAIN. LE. 0.)INFILT=RAIN
359.  77 CONTINUE
360.  **** 18)  CALCULATION OF NET FLOW OF HEAT AND NET FLUX OF WATER
361.      FLUX(1)=INFILT-EVAP
362.      DO 100 I = 1,NL
363.          NFLOW(I) = FLOW(I) - FLOW(I+1)
364.          NFLUX(I)=FLUX(I)-FLUX(I+1)
365.  100 CONTINUE

```

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366. **** 19) INTEGRATION OF VOLUMETRIC HEAT CONTENT AND VOLUMETRIC
367. **** WATER CONTENT
368. VOLHI=INTGRL(IVOLHI,NFLOW1,13)
369. VOLWI=INTGRL(IVOLWI,NFLUX1,13)
370. **** 20) CALCULATION OF CUMULATIVE RAIN, INFILTRATION, EVAPORATION
371. **** AND DRAINAGE
372. CUMRN = INTGRL (0.0 , RAIN)
373. CUMINF = INTGRL ( 0.0 , INFILT )
374. CUMEVP = INTGRL ( 0.0 , EVAP )
375. CUMDRN = INTGRL ( 0.0 , FLUX(NLL))
376. **** 21) CALCULATION OF TOTAL WATER FOR DIFFERENT LAYERS
377. CUMWTR = 0.0
378. CUMWT1 = 0.0
379. CUMWT2 = 0.0
380. CUMWT3 = 0.0
381. DO 110 I=1,NL
382. CUMWTR= CUMWTR + VOLW(I)
383. 110 CONTINUE
384. DO 120 I=6,NL
385. CUMWT1 = CUMWT1 + VOLW(I)
386. 120 CONTINUE
387. DO 130 I=9,NL
388. CUMWT2 = CUMWT2 + VOLW(I)
389. 130 CONTINUE
390. DO 140 I=12,NL
391. CUMWT3 = CUMWT3 + VOLW(I)
392. 140 CONTINUE
393. **** 22) CALCULATION OF DAILY TOTALS
394. ZBHJS=IMPULS(86400.,86400.)
395. IF(ZBHJS.LT.0.5) GO TO 88
396. INF(DNUM 1)=CUMINF
397. RN(DNUM-1)=CUMRN
398. EVP(DNUM-1)=CUMEVP
399. DRAIN(DNUM-1)=CUMDRN
400. DINF=CUMINF-INF(DNUM-2)
401. DRN=CUMRN-RN(DNUM-2)
402. DEVP=CUMEVP-EVP(DNUM-2)
403. DDRN=CUMDRN-DRAIN(DNUM-2)
404. 88 CONTINUE
405. **** 23) CHECK WATER BALANCE
406. BALANS = CUMWTR - IWATER - CUMINF + CUMEVP + CUMDRN
407. **** 24) OUTPUT OF DESIRED VARIABLES
408. Z=IMPULS(28800.0,86400.)
409. IF(Z.LT.0.5) GO TO 99
410. 222 CONTINUE
411. WRITE(6,1300) WINPUT(1,DNUM),TIME, XDNUM,STIME
412. 1300 FORMAT(' JULIAN DAY NUMBER = ',F4.0,' TIME = ',F10.1,
413. $ ' XDNUM = ',F11.0,' STIME = ',F7.4)
414. WRITE(6,1400)
415. 1400 FORMAT('0 I ',5X,'DEPTH',10X,'THETA',11X,'PPOT',11X,
416. $ 'FLUX',9X,'NET FLUX',10X,'TEMP')
417. DO 150 I=1,NL
418. 150 WRITE(6,1500) I,DEPTH(I),THETA(I),PPOT(I),FLUX(I), ...
419. NFLUX(I),TEMP(I)
420. 1500 FORMAT( 13,6E15.4)
421. WRITE(6,1600)
422. 1600 FORMAT(1H ////)
423. GO TO 111
424. 99 CONTINUE
425. ZZ=IMPULS(57600.,86400.)
426. IF(ZZ.LT.0.5) GO TO 111

```

```

427.          GO TO 222
428.          111 CONTINUE
429.          *****
430.          ****
431.          **** E.....TERMINAL SECTION
432.          ****
433.          TERMINAL
434.          *****
435.          TIMER F'NTIM=259200.0,PRDEL=86400.0,DELT=100.0
436.          PRINT JDNUM, XDNUM, DRN, DINF, DEVP, DDRN, CUMWTR,...
437.          CUMWT1, CUMWT2, CUMWT3, BALANS, CUMRN,CUMDRN,CUMINF,CUM EVP,...
438.          FLOW(14)
439.          METHOD TRAPZ
440.          END
441.          *
442.          *
443.          *
444.          * WEATHER INPUT DATA, STORED IN ARRAY WINPUT(11,37)
445.          * JNM DL DGR TMAX TMIN DMAX DMIN SA BEGIN END RFT
446.          INPUT
447.             1. 10.70 10.0 16.0 0.5 3.0 -2.5 3.0 0.0 0.0 0.0
448.             2. 10.70 10.0 16.0 0.5 3.0 -2.5 3.0 9.0 12.0 25.0
449.             3. 10.70 10.0 16.0 0.5 3.0 -2.5 3.0 0.0 0.0 0.0
450.             4. 10.70 10.0 16.0 0.5 3.0 -2.5 3.0 0.0 0.0 0.0
451.             5. 10.70 10.0 16.0 0.5 3.0 -2.5 3.0 0.0 0.0 0.0
452.             6. 10.70 10.0 16.0 0.5 3.0 -2.5 3.0 0.0 0.0 0.0
453.             7. 10.70 10.0 16.0 0.5 3.0 -2.5 3.0 0.0 0.0 0.0
454.             8. 10.70 10.0 16.0 0.5 3.0 -2.5 3.0 0.0 0.0 0.0
455.             9. 10.70 10.0 16.0 0.5 3.0 -2.5 3.0 0.0 0.0 0.0
456.            10. 10.70 10.0 16.0 0.5 3.0 -2.5 3.0 0.0 0.0 0.0
457.            11. 10.70 10.0 16.0 0.5 3.0 -2.5 3.0 0.0 0.0 0.0
458.            12. 10.70 10.0 16.0 0.5 3.0 -2.5 3.0 0.0 0.0 0.0
459.            13. 10.70 10.0 16.0 0.5 3.0 -2.5 3.0 0.0 0.0 0.0
460.            14. 10.70 10.0 16.0 0.5 3.0 -2.5 3.0 0.0 0.0 0.0
461.            15. 10.70 10.0 16.0 0.5 3.0 -2.5 3.0 0.0 0.0 0.0
462.             0. 10.70 10.0 16.0 0.5 3.0 -2.5 3.0 0.0 0.0 0.0
463.          ENDINPUT
464.          STOP
465.          ENDJOB
466.          /*END

```

## APPENDIX C - CALCULATION OF UNSATURATED HYDRAULIC CONDUCTIVITY

## CALCULATION OF UNSATURATED HYDRAULIC CONDUCTIVITY

PURPOSE: This WATFIV program is designed to calculate the unsaturated hydraulic conductivity as a function of water content using Jackson's method (Jackson, 1972; Bouwer and Jackson, 1974). It also states the relationship between water content vs. pressure potential and water content vs. hydraulic conductivity in the form required for a CSMP III FUNCTION statement. Note, that the symbols used for variables in this program are different from those used in the general model.

INTRODUCTION: In order to use this program, three parameters must be known. These are:

1. the saturated hydraulic conductivity of the soil, (COND(1)), in m/s,
2. The relationship between pressure potential, (PP(I)), in m water column and volumetric water content, (TH(I)), and
3. the maximum value of water content, (TH(1)).

The first two parameters are obtained experimentally and the third one is estimated by calculating the porosity of the soil, i.e.

$$TH(1) = \text{porosity} = 1 - DB/PD$$

where DB is the dry bulk density of the soil in  $\text{g/cm}^3$ , and PD is the particle density of the soil, usually taken as  $2.65 \text{ g/cm}^3$ .

It should be noted that Jackson's method requires detailed information on the relationship between pressure potential vs. water content for high values of pressure potential, i.e.  $> -0.50 \text{ m}$ .

Experience has shown that this information has a critical effect on the results.

PROCEDURE: This section outlines the procedure that should be followed to obtain the values of pressure potential for different values of water content from experimental data.

1. Plot the relationship between pressure potential vs. volumetric water content for values of pressure potential  $> -5.0$  m on a linear scale. To the value of 0.0 pressure potential assign the maximum water content (TH(1)). A semi-log graph of pressure potential vs. water content is used for the remaining values of pressure potential.

2. Select an increment for the volumetric water content (DELTH), i.e. 0.01, 0.02.

3. Calculate the number of values of water content (M) for which the hydraulic conductivity is to be calculated.

$$M = \frac{TH(\text{MAXIMUM}) - TH(\text{MINIMUM})}{DELTH} + 1.0$$

4. From the graphs, read the values of pressure potential that correspond to the midpoint of each equal increment of volumetric water content. This is illustrated with an example.

EXAMPLE: DELTH = 0.02, TH(1) = 0.42

<u>WATER CONTENT INTERVAL</u>	<u>MIDPOINT</u>	<u>PP(I) (-m)</u>
0.42 - 0.40	0.41	0.07
0.40 - 0.38	0.39	0.22
0.38 - 0.36	0.37	0.60
.	.	.
.	.	.
.	.	.
0.04 - 0.02	0.03	29000.00

INPUT TO THE WATFIV PROGRAM: The following input cards must be specified, in the sequence given, after the //\$DATA card.

<u>DATA CARD NO.</u>	<u>IDENTIFICATION</u>	<u>RESTRICTIONS</u>
1.	TITLE	up to 80 alphabetic or numeric charaters
2.	TH(1)	Real variable
3.	DELTH	Real variable
4.	M	Integer
5.	PP(1)	Positive real variables
I+4	PP(I)	.
.	.	.
M+4	PP(M)	.
M+5	COND(1)	Real variable

OUTPUT: The output of the program is in three parts. The first part lists the title and the input data. Note that in the first table the values of PP(I), LOG10 PP(I), and RH(I) correspond to THETAM(I), the midpoint water content. The second part lists the results. Note that in the second table the calculated value of hydraulic conductivity, (COND(I)), corresponds to THETA(I). The maximum hydraulic conductivity (COND(1)) should correspond to the maximum value of water content (TH(1)). The third part is a table of volumetric water content vs. pressure potential, and volumetric water content vs. hydraulic conductivity, in the form required for a CSMP FUNCTION statement.

REFERENCES:

1. Bouwer, H. and R.D. Jackson. 1974. Determining soil properties. p. 611-672. In: Jan van Schilfgaarde (Ed). Drainage for Agriculture. Agronomy Monograph 17. American Society of Agronomy, Madison, WI.
2. Jackson, R.D. 1972. On the calculation of hydraulic conductivity. Soil Sci. Soc. Amer. Proc. 36: 380-382.



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1. //JACKSON JOB (R042,402E,*02,001,PL), LASCANO
2. /*WATFIV
3. C
4. C
5. C CALCULATE HYDPAULIC CONDUCTIVITY
6. C JACKSON 1972 SSAP 36 : 390-382
7. C
8. C
9. C*****
10. C THE NECESSARY INPUT FOR THIS CALCULATION IS GIVEN BELOW
11. C THE EXPLANATION OF INPUT VARIABLES IS GIVEN IN THE PROGRAM
12. C
13. C
14. C DATA CARD 1 IDENTIFICATION
15. C 1.....TITLE
16. C 2.....TH (1)
17. C 3.....DELTH
18. C 4.....M
19. C 5.....PP (1)
20. C .
21. C .
22. C .
23. C I+4.....PP (I)
24. C .
25. C .
26. C .
27. C M+4.....PP (M)
28. C M+5.....COND(1)
29. C
30. C*****
31. REAL NOMI, NOMJ, LCOND, LPP
32. INTEGER TITLE(40)
33. DIMENSION TH(70), PP(70), RELCON(70), COND(70), LCOND(70), PH(70)
34. DIMENSION LPP(70), THETAM(70), THX(70), CONDX(70), PPX(70), THY(70)
35. C
36. C INPUT DATA
37. C
38. C READ TITLE (NAME OF SOIL, DEPTH, OTHER INFORMATION)
39. READ(5,11) TITLE
40. 11 FORMAT(20A1)
41. C MAXIMUM VALUE OF WATER CONTENT
42. READ, TH(1)
43. C DEFINE STEP SIZE (INCREMENT)
44. READ, DELTH
45. C M IS THE TOTAL NUMBER OF VALUES OF WATER CONTENT FOR WHICH THE
46. C HYDRAULIC CONDUCTIVITY IS CALCULATED
47. C M CAN BE CALCULATED FROM THE FOLLOWING EXPRESSION:
48. C  $M = (TH(MAXIMUM) - TH(MINIMUM)) / DELTH + 1.0$ 
49. READ, M
50. C
51. C PROGRAM
52. C
53. DO 10 I = 1, M
54. TH(I) = TH(1) - (I-1)*DELTH
55. THETAM(I) = TH(I) - (DELTH/2.0)
56. C READ PRESSURE POTENTIAL VALUES IN M, CORRESPONDING TO THEIR
57. C RESPECTIVE VALUES FOR THE CENTER OF EACH INCREMENT THETA.
58. READ, PP(I)
59. PP(I) = -PP(I)
60. RH(I) = EXP(PP(I)/14091.)

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61.      LPP(I) = ALOG10(-PP(I))
62.      10 CONTINUE
63.      DENOM = 0.
64.      DO 20 J = 1,M
65.      DENOMJ = (2*J-1)/(PP(J)**2)
66.      DENOM = DENOM + DENOMJ
67.      20 CONTINUE
68.      C      GIVE MAXIMUM CONDUCTIVITY IN M/S (SAT. CONDUCTIVITY).
69.      READ, COND(1)
70.      C      RECORD OF INPUT DATA
71.      WRITE(6,850) TITLE
72.      850  FORMAT('1',//,20X,'TITLE:',80A1,/)
73.      WRITE(6,900)
74.      900  FORMAT('1',//,45X,'INPUT DATA',/)
75.      WRITE(6,1000) TH(1)
76.      1000  FORMAT('1',20X,'MAXIMUM VALUE OF WATER CONTENT =',F4.2)
77.      WRITE(6,1100) DELTH
78.      1100  FORMAT('1',20X,'INCREMENT OF WATER CONTENT =',F5.3)
79.      WRITE(6,1200) M
80.      1200  FORMAT('1',20X,'NUMBER OF VALUES OF WATER CONTENT, FOR WHICH K IS
81.      $CALCULATED = ',I3)
82.      WRITE(6,1300) COND(1)
83.      1300  FORMAT('1',20X,'MAXIMUM CONDUCTIVITY (SAT. COND.) =',E14.5
84.      $,2X,'M/S')
85.      WRITE(6,1400)
86.      1400  FORMAT('0',20X,'THE VALUES OF THETAM ARE THE MIDPOINTS',/,
87.      $21X,'OF EACH INCREMENT TO WHICH THE VALUES OF PP(I)',/,
88.      $21X,'CORRESPOND ACCORDING TO EXPERIMENTAL DATA')
89.      WRITE(6,1450)
90.      1450  FORMAT('0',20X,'THE LOG10 VALUE OF PP(I) AND RH(I) CORRESPOND',
91.      $/,21X,'TO THE VALUE OF THETAM(I)',////)
92.      WRITE(6,1500)
93.      1500  FORMAT('1',20X,'THETA(I)',2X,'THETAM(I)',4X,'PP(I) (M)',2X,
94.      $'LOG10 PP(I)',2X,'RH(I)')
95.      DO 50 I=1,M
96.      WRITE(6,1600) TH(I),THETAM(I),PP(I),LPP(I),RH(I)
97.      1600  FORMAT(' ',23X,F4.2,6X,F4.2,5X,F9.2,6X,F6.2,2X,F6.2)
98.      50 CONTINUE
99.      DO 30 I = 1,M
100.      NOMI = 0.
101.      DO 40 J = 1,M
102.      NOMJ = (2*J + 1 - 2*I)/(PP(J)**2)
103.      NOMI = NOMI + NOMJ
104.      40 CONTINUE
105.      RELCON(I) = (TH(I)/TH(1))*(NOMI /DENOM)
106.      COND(I) = RELCON(I)*COND(1)
107.      LCOND(I) = ALOG10(COND(I))
108.      30 CONTINUE
109.      WRITE(6,1700)
110.      1700  FORMAT('1',////////,45X,'RESULTS',/)
111.      WRITE(6,1800)
112.      1800  FORMAT('1',20X,'THETA(I)',4X,'RELCON(I)',4X,'COND(I)',4X,
113.      $'LOG10 COND(I)')
114.      DO 60 I=1,M
115.      WRITE(6,1900) TH(I),RELCON(I),COND(I),LCOND(I)
116.      1900  FORMAT(' ',21X,F6.4,4X,E10.4,3X,E10.4,4X,F6.2)
117.      60 CONTINUE
118.      WRITE(6,2000)
119.      2000  FORMAT(1H1)
120.      K=0
121.      DO 90 J=1,M

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122.          KK=N-K
123.          THX(J)=THETAM(KK)
124.          CONDX(J)=COND(KK)
125.          THY(J)=TH(KK)
126.          PPX(J)=PP(KK)
127.          K=K+1
128.          9C CONTINUE
129.          WRITE(6,2100)
130.          2100 FORMAT(1H1)
131.          DO 100 J=1,M
132.          WRITE(6,2200) THX(J),PPX(J)
133.          2200 FORMAT(' ',20X,'(',F6.3,',',F10.2,')',...')
134.          100 CONTINUE
135.          WRITE(6,2300)
136.          2300 FORMAT(1H1)
137.          DO 110 J=1,M
138.          WRITE(6,2400) THY(J),CONDX(J)
139.          2400 FORMAT(' ',20X,'(',F6.3,',',E14.7,')',...')
140.          110 CONTINUE
141.          WRITE(6,2500)
142.          2500 FORMAT(1H1)
143.          STOP
144.          END
145.          // $DATA
146.          NORWOOD SILT LOAM, AGRONOMY FARM, 0.00 - 0.20 M DEPTH
147.          0.42
148.          0.020
149.          20
150.          0.07
151.          0.22
152.          0.60
153.          1.20
154.          3.60
155.          7.20
156.          11.0
157.          18.0
158.          30.0
159.          45.0
160.          74.0
161.          160.0
162.          370.0
163.          700.0
164.          1500.0
165.          3000.0
166.          6000.0
167.          10000.0
168.          16000.0
169.          29000.0
170.          5.0E-07
171.          /*END

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TITLE: NORWOOD SILT LOAM, AGRONOMY FARM, 0.00 - 0.20 M DEPTH

# INPUT DATA

MAXIMUM VALUE OF WATER CONTENT =0.42

INCREMENT OF WATER CONTENT =0.020

NUMBER OF VALUES OF WATER CONTENT, FOR WHICH K IS CALCULATED =

MAXIMUM CONDUCTIVITY (SAT. COND.) = 0.50000E-06 K/S

THE VALUES OF THETAM ARE THE MIDPOINTS  
OF EACH INCREMENT TO WHICH THE VALUES OF PP(I)  
CORRESPOND ACCORDING TO EXPERIMENTAL DATA

THE LOG10 VALUE OF PP(I) AND PH(I) CORRESPOND  
TO THE VALUE OF THETAM(I)

THETA (I)	THETAM (I)	PP (I) (M)	LOG10 PP (I)	RH (I)
0.42	0.41	-0.07	-1.15	1.00
0.40	0.39	-0.22	-0.66	1.00
0.38	0.37	-0.60	-0.22	1.00
0.36	0.35	-1.20	0.08	1.00
0.34	0.33	-3.60	0.56	1.00
0.32	0.31	-7.20	0.86	1.00
0.30	0.29	-11.00	1.04	1.00
0.28	0.27	-18.00	1.26	1.00
0.26	0.25	-30.00	1.48	1.00
0.24	0.23	-45.00	1.65	1.00
0.22	0.21	-74.00	1.87	0.99
0.20	0.19	-160.00	2.20	0.99
0.18	0.17	-370.00	2.57	0.97
0.16	0.15	-700.00	2.85	0.95
0.14	0.13	-1500.00	3.18	0.90
0.12	0.11	-3000.00	3.48	0.81
0.10	0.09	-6000.00	3.78	0.65
0.08	0.07	-10000.00	4.00	0.49
0.06	0.05	-16000.00	4.20	0.32
0.04	0.03	-29000.00	4.46	0.13

# RESULTS

THETA (I)	RELCON (I)	COND (I)	LOG10 COND (I)
0.4200	0.1000E-01	0.5000E-06	-6.30
0.4000	0.1111E-00	0.5553E-07	-7.26
0.3800	0.1746E-01	0.8728E-08	-8.06
0.3600	0.3388E-02	0.1694E-08	-8.77
0.3400	0.6131E-03	0.3065E-09	-9.51
0.3200	0.1993E-03	0.9915E-10	-10.00
0.3000	0.7182E-04	0.3591E-10	-10.44
0.2800	0.2480E-04	0.1240E-10	-10.91
0.2600	0.8391E-05	0.4196E-11	-11.38
0.2400	0.2625E-05	0.1313E-11	-11.88
0.2200	0.6530E-06	0.3265E-12	-12.49
0.2000	0.1265E-06	0.6313E-13	-13.20
0.1800	0.2527E-07	0.1263E-13	-13.90
0.1600	0.5693E-08	0.2846E-14	-14.55
0.1400	0.1207E-08	0.6033E-15	-15.22
0.1200	0.2823E-09	0.1411E-15	-15.85
0.1000	0.7131E-10	0.3566E-16	-16.45
0.0800	0.1843E-10	0.9215E-17	-17.04
0.0600	0.3734E-11	0.1867E-17	-17.73
0.0400	0.3961E-12	0.1980E-18	-18.70

( 0.030,	-29000.00),	...
( 0.050,	-16000.00),	...
( 0.070,	-10000.00),	...
( 0.090,	-6000.00),	...
( 0.110,	-3000.00),	...
( 0.130,	-1500.00),	...
( 0.150,	-700.00),	...
( 0.170,	-370.00),	...
( 0.190,	-160.00),	...
( 0.210,	-74.00),	...
( 0.230,	-45.00),	...
( 0.250,	-30.00),	...
( 0.270,	-18.00),	...
( 0.290,	-11.00),	...
( 0.310,	-7.20),	...
( 0.330,	-3.60),	...
( 0.350,	-1.20),	...
( 0.370,	-0.60),	...
( 0.390,	-0.22),	...
( 0.410,	-0.07),	...

( 0.040, 0.1980432E-18), ...  
 ( 0.060, 0.1867095E-17), ...  
 ( 0.080, 0.9215115E-17), ...  
 ( 0.100, 0.3565605E-16), ...  
 ( 0.120, 0.1411493E-15), ...  
 ( 0.140, 0.6032844E-15), ...  
 ( 0.160, 0.2846457E-14), ...  
 ( 0.180, 0.1263317E-13), ...  
 ( 0.200, 0.6312881E-13), ...  
 ( 0.220, 0.3265092E-12), ...  
 ( 0.240, 0.1312614E-11), ...  
 ( 0.260, 0.4195633E-11), ...  
 ( 0.280, 0.1239914E-10), ...  
 ( 0.300, 0.3590753E-10), ...  
 ( 0.320, 0.9914647E-10), ...  
 ( 0.340, 0.3065372E-09), ...  
 ( 0.360, 0.1694214E-08), ...  
 ( 0.380, 0.8728055E-08), ...  
 ( 0.400, 0.5553067E-07), ...  
 ( 0.420, 0.5000000E-06), ...